



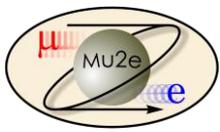
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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

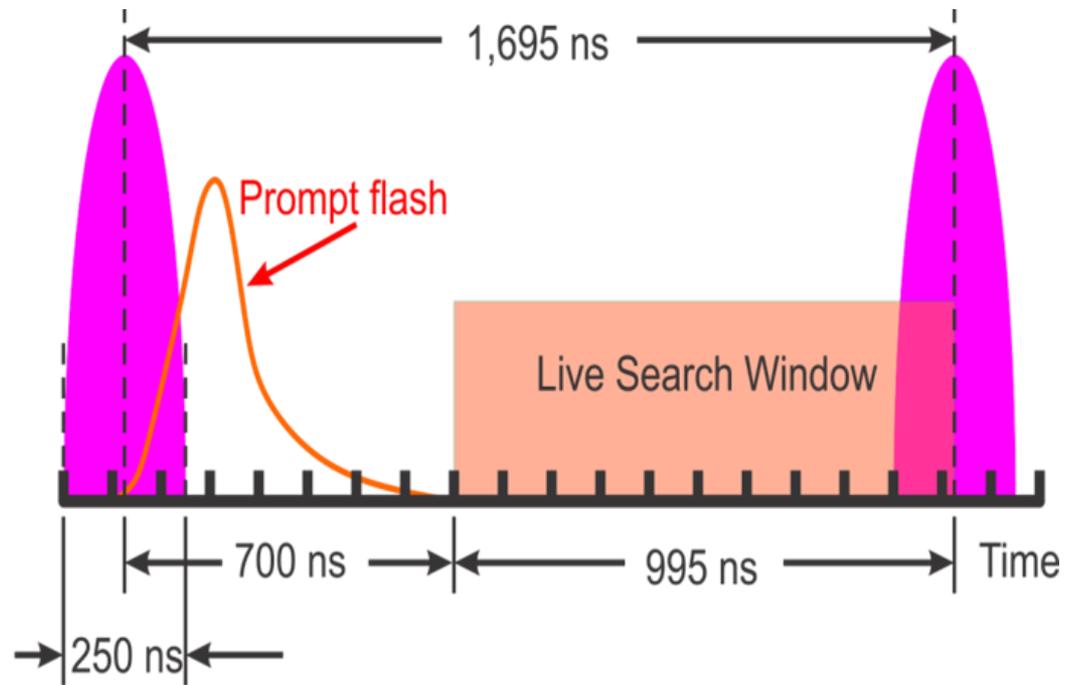
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# **Technical Design of the Resonant Extraction for the Mu2e experiment**

Vladimir Nagaslaev  
Technical Design Peer Review  
August 25-27, 2015



# Introduction: Motivation



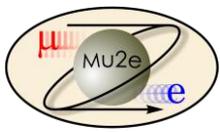
Mu2e Experiment:

Pulsed beam

Detector dead time - 700ns

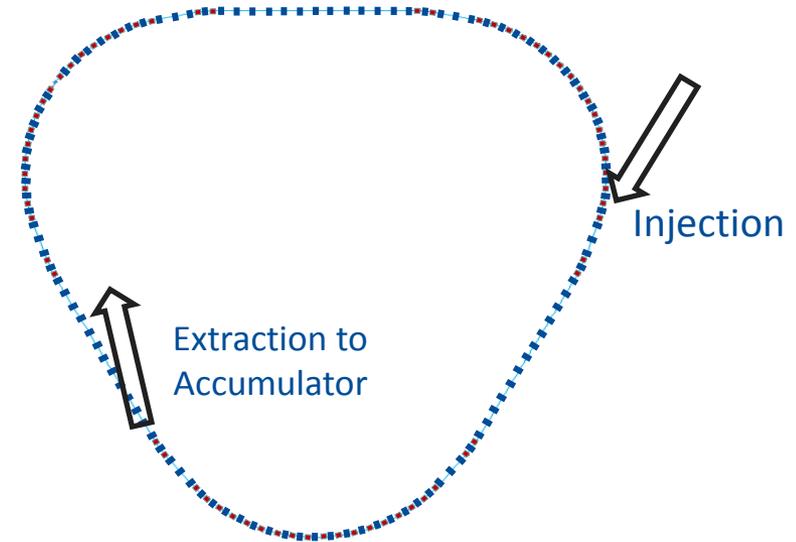
Detector Live time - 995ns

Slow extraction is important to deliver this time structure

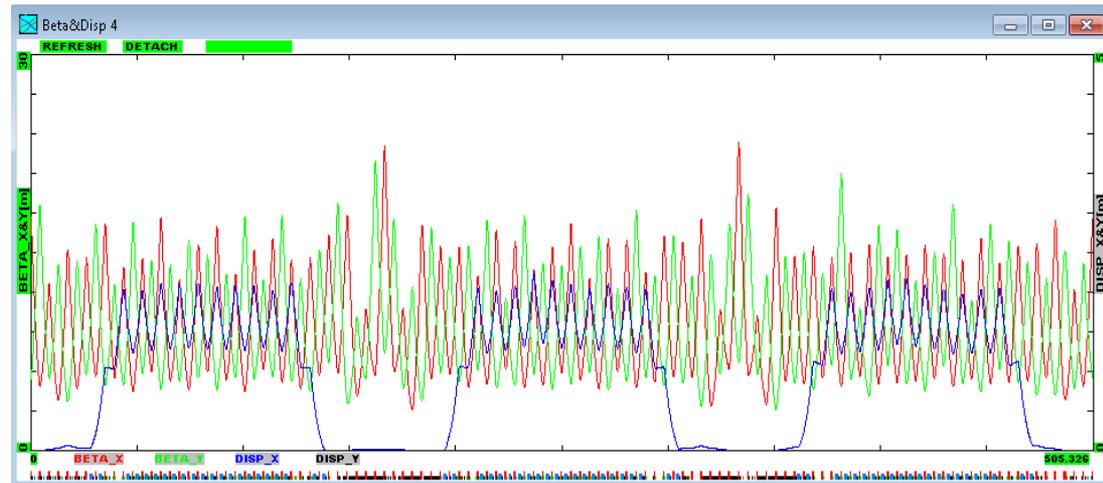


# Introduction: Debuncher Ring

<b>Circumference</b>	<b>505m</b>
#FODO cells	57
Max Beta	15m
Operating point	<b>9.763 / 9.769</b>
Max Intensity	3e8 p
Acceptance (unnorm.)	36 $\pi\mu$

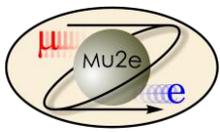


- Regular FODO, 60° per cell
- Zero Dispersion in SS
- Betas optimized for aperture
- Rapid 6D stochastic cooling
- RF bunch rotation/debunching
- Transfer to Accumulator



Debuncher lattice functions

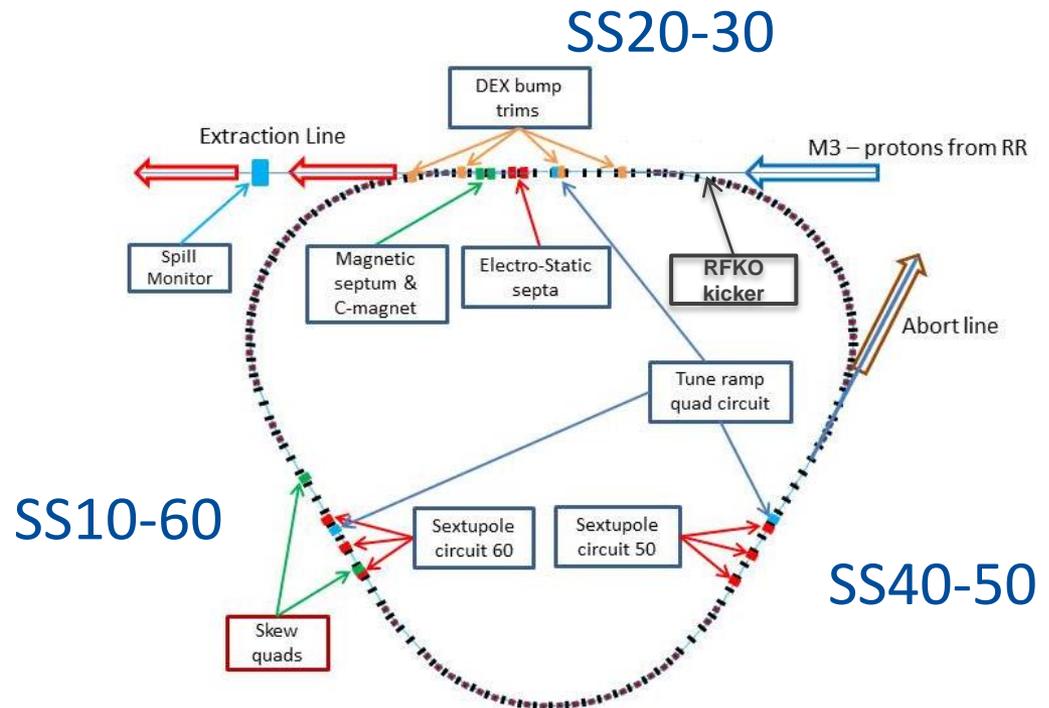


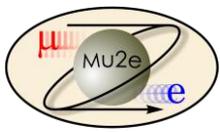


# Implementation of RE in the DR

- New injection point
- Extraction in SS30
- ESS
- 2 families of Sext.
- A family of tune Quads
- Magnetic septa
- Dynamic orbit control
- Abort line
- RFKO system
- Spill monitoring
- Spill regulation

- 3<sup>rd</sup> Integer resonance
- $Q_x/Q_y=9.650/9.735$





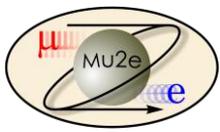
# Requirements

## Mu2e Proton Beam Requirements (doc-1105)

Parameter	Design	Limit
Length of slow spill period	54 ms	>20 ms
Average intensity per pulse on target	31 Mp	<50 Mp
Maximum variation of pulse intensity on target	$\pm 50\%$	$\pm 50\%$

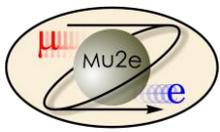
## Additional Requirements

<b>Extraction efficiency</b>	<b>98%</b>	
Unextracted left over	<5%	



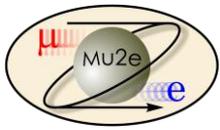
# Beam scenario in the Delivery Ring (DR)

Parameter	Value	Units
MI Cycle time	1.333	sec
Number of spills per MI cycle	8	
Number of protons per micro-pulse	$3.1 \times 10^7$	protons
Maximum DR Beam Intensity	$1.0 \times 10^{12}$	protons
Instantaneous spill rate	$18.5 \times 10^{12}$	protons/sec
Average spill rate	$6.0 \times 10^{12}$	protons/sec
Duty Factor (Total Spill Time $\div$ MI Cycle Length)	32	%
Duration of each spill	54	msec
Spill On Time per MI cycle	497	msec
Spill Off Time per MI cycle	836	msec
Time Gap between spills	5	msec



# Technical and operational risks

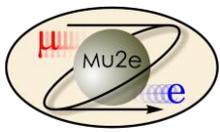
1. Technical Risks (extraction specific)
  - a. High losses
    - Large effective thickness of ESS planes
    - Insufficient kick in the ESS
    - Inadequate ESS alignment
    - Inadequate orbit control
  - b. High spill variations
    - Regulation is not fast enough
    - Regulation is not deep enough
    - Insufficient RFKO power
  - d. Insufficient aperture
  - e. Magnet strengths are not sufficient
  - f. Magnet ramping capabilities are insufficient
  - g. Insufficient machine diagnostics
  - h. Substantial fraction of the beam not extracted
  - i. Beam instabilities
2. Operational risks
  - a. Radiation and machine protection



# Path to satisfy the requirements and address risks

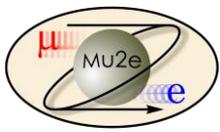
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- **Develop the model/design**
  - Determine the optimal parameter space
  - Determine necessary hardware and specifications
  - Identify key elements of the design that are necessary to satisfy requirements
  - Satisfy machine stability conditions
- **Verify design: simulations/prototyping/beam-tests**
- **Prepare the Ring (aperture, diagnostics, lattice)**
- **Ensure fabrication/installation satisfy the specs**
  
- **Address risks:**
  - Evaluate and reserve back up options when appropriate
  - Include in the design or pre-mitigate when necessary



## Physics model of the Resonant Extraction

- Theoretical model
- Simplified parametric model
- Tracking simulations
  - Orbit
  - Synergia
  - MARS
- Beam studies
- Machine operation issues
  - Stability
  - Optics design



# Theoretical model of Resonant Extraction

L.Michelotti: "Preliminaries toward studying resonant extraction from the Debuncher", 2010

Hamiltonian: 
$$H = \Delta\nu \cdot a \cdot a^* - i g a^3 + i g^* a^{*3} + \dots = \Delta\nu I - (g \cdot e^{-3i\phi} + g^* \cdot e^{3i\phi}) I^{3/2} + \dots$$

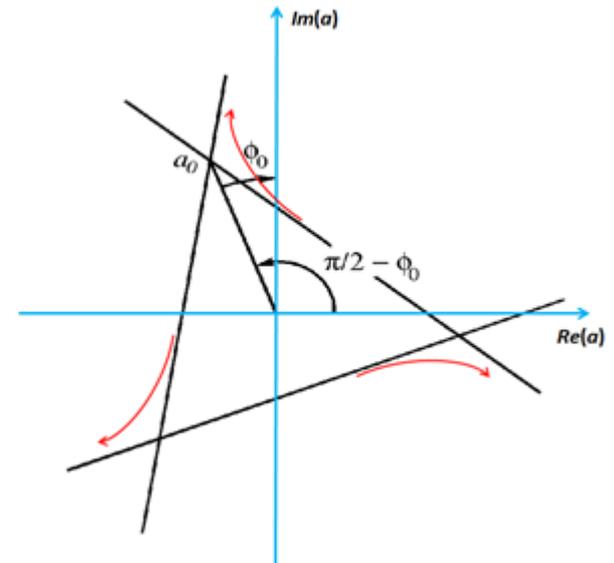
with: 
$$a = \sqrt{I} \cdot e^{i\varphi} = \frac{x + i(\alpha x + \beta x')}{\sqrt{2\beta}} \quad \text{and} \quad g = \frac{i}{6\sqrt{2}} \frac{1}{4\pi} \sum e^{in\theta} \left( \frac{B'' L}{B\rho} \beta^{3/2}(\theta) \cdot e^{-3i(\psi_x(\theta) - \Delta\nu\theta)} \right)$$

Separatrix conditions:

$$|a_0| = \sqrt{I_0} = \left| \frac{\Delta\nu}{3g} \right| \quad \varphi_0 = \frac{\arg(g)}{3}$$

For optimal orientation  $\phi_0 = -\pi/6$ :

$$a = a_0 \cdot (1 + r \cdot e^{i\pi/6})$$





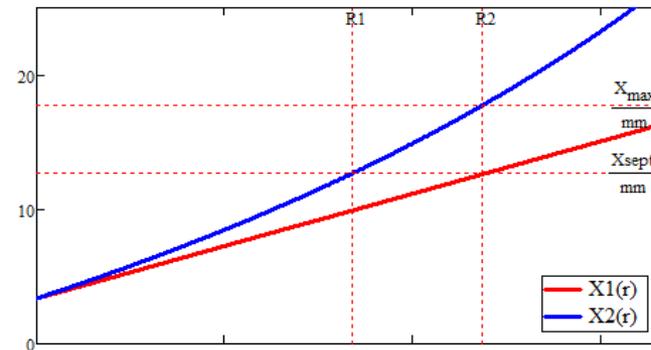
# Parametric model of the RE, application

## Semi-analytical extension of the model:

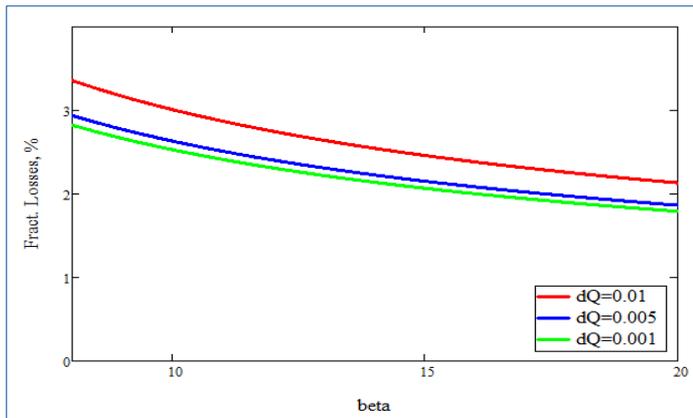
V.Nagaslaev, L.Michelotti: "Parameter Space Optimization For The Third Integer Resonant Extraction.", 2012

$$R_L = \frac{d_w}{X_S^2 - X_0^2} \frac{2X_0}{\ln \left( \frac{X_{\max} - X_0}{X_{\max} + X_0} \frac{X_S + X_0}{X_S - X_0} \right)}$$

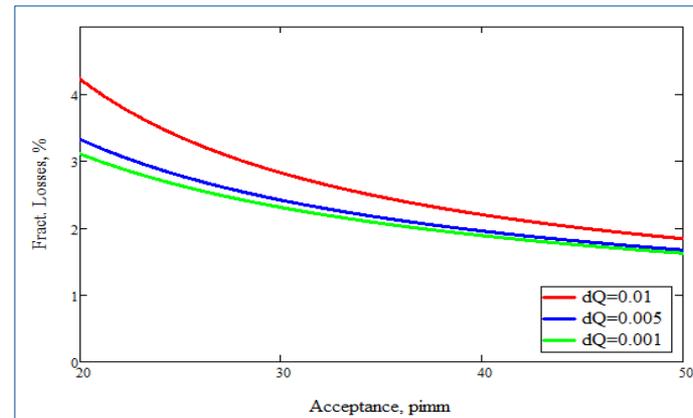
$$R_L = R(t, \beta, \varepsilon, Ap)$$



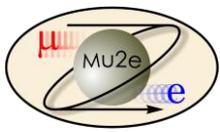
Current x-position  $X_1$  and x-position after 3 turns,  $X_2$  as functions of parameter  $r$ .



Geometrical losses vs beta-function at ESS



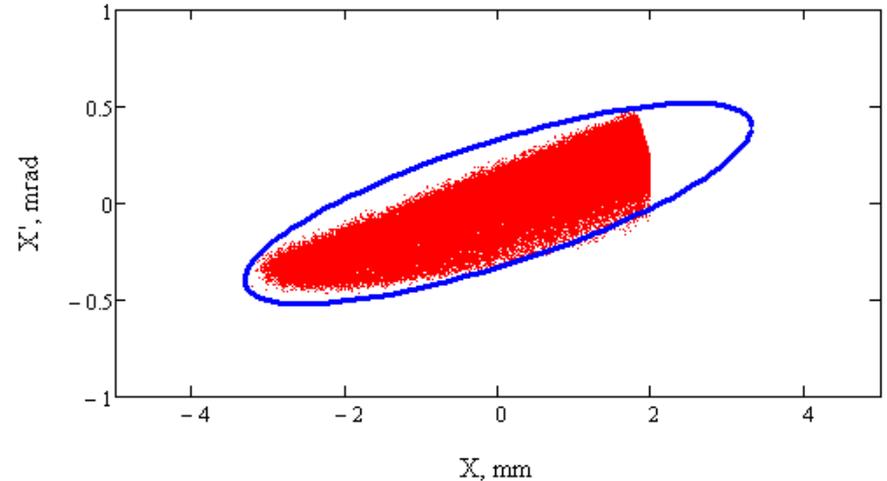
Geometrical losses vs machine acceptance



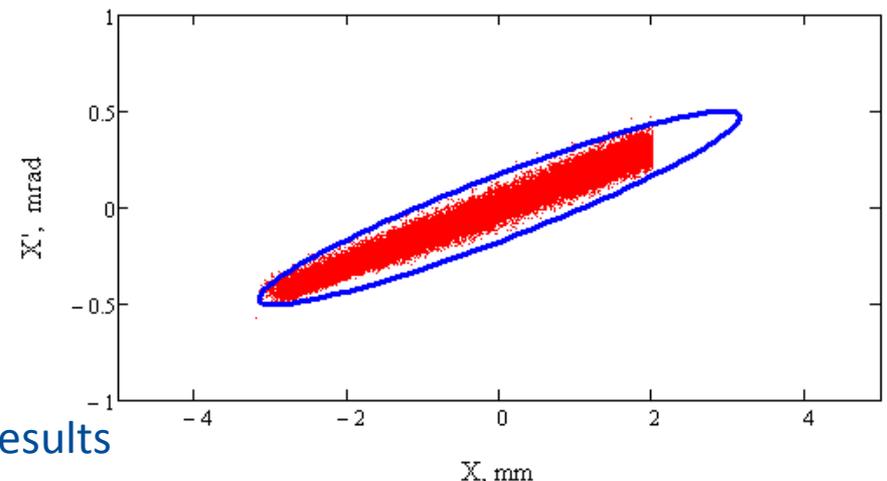
# Synergia tracking simulations

- We adopted Synergia package for the tracking simulations:
  - RF fields; RFKO fields
  - DEX bump with ramping
  - Tune ramping; full spill tracking
  - Aperture definition
  - Substantial speed up
- Main results include:
  - Full spill simulations
  - Ramping curves
  - Extracted beam samples at ESS
  - DEX bump optimization
  - RFKO heating rates

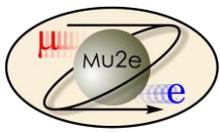
Performance benchmarked with earlier ORBIT results  
No known physics observed to impact performance.



Extracted beam footprint, DEX bump off



Extracted beam footprint, DEX bump on

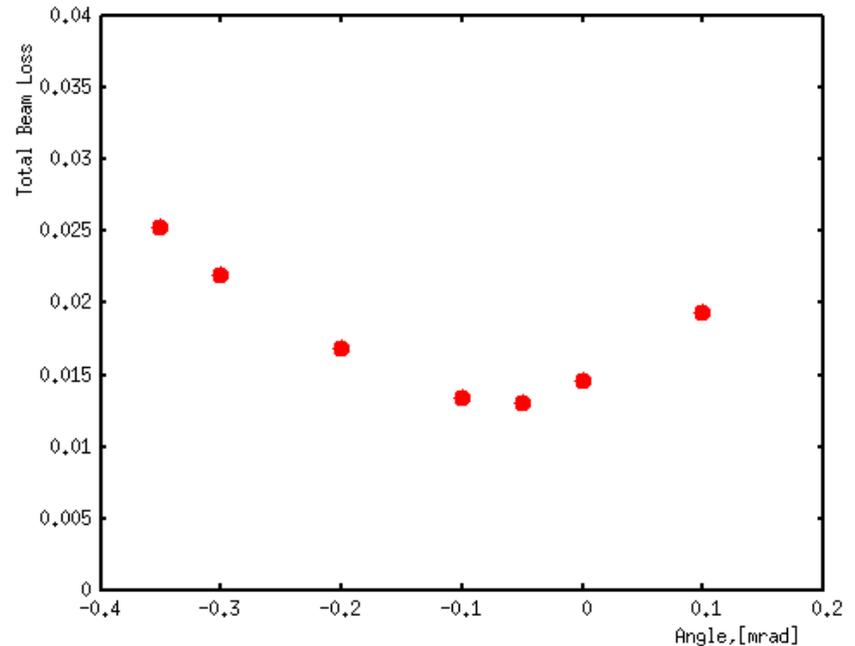


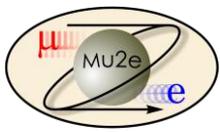
# Tracking simulations with MARS

- Tracking extracted beam with MARS code:
  - ✓ Tracking particles in media and DC fields
  - ✓ Radiation levels, Residual activation, Energy deposition, etc
  - ✓ Essential for beam loss calculations and geometry optimization

## Plot:

- Total beam losses
- Narrow angle spread beam
- Losses vs beam misalignment

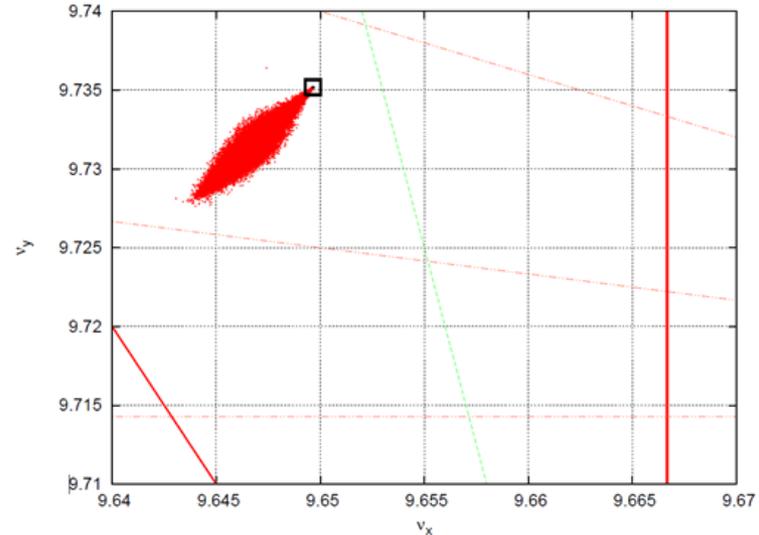




# Machine operation issues: Space Charge (SC)

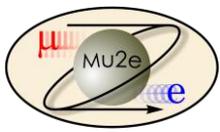
Laslett tune shift:

$$Q_{sc} = \frac{N_b r_p T_0}{2(2\pi)^{3/2} \gamma^2 \epsilon_n \tau_b} \rightarrow 0.01$$



With dispersive effects  $Q_{SC} \rightarrow 0.007$

Not an issue if approaching the resonance from below



# Machine operation issues: Instabilities

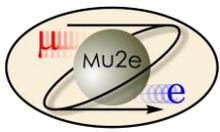
- DR intensity increases  $\sim 10^5$

- Instabilities?

*[ A.Burov , BeamStability\_Mu2e.pdf ]*

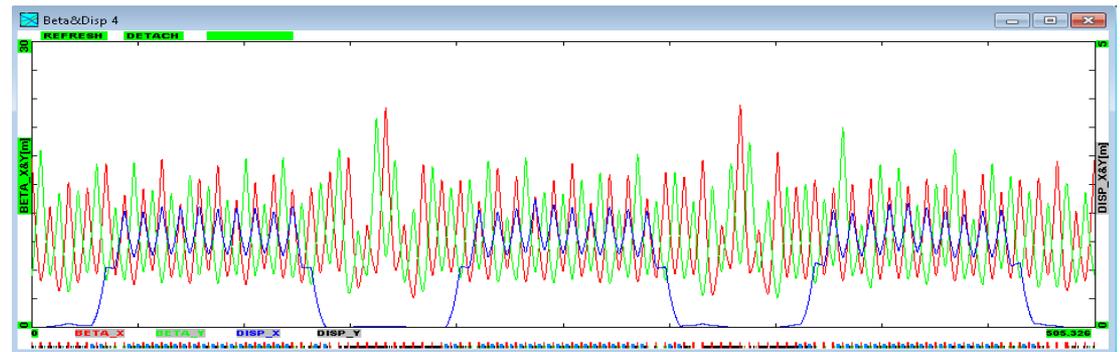
- TMCI
- Weak head-tail
- Electron cloud
- Microwave
- IBS

Considered in much more challenging version of Mu2e with 24kW beam power. Not nearly an issue for the 8kW

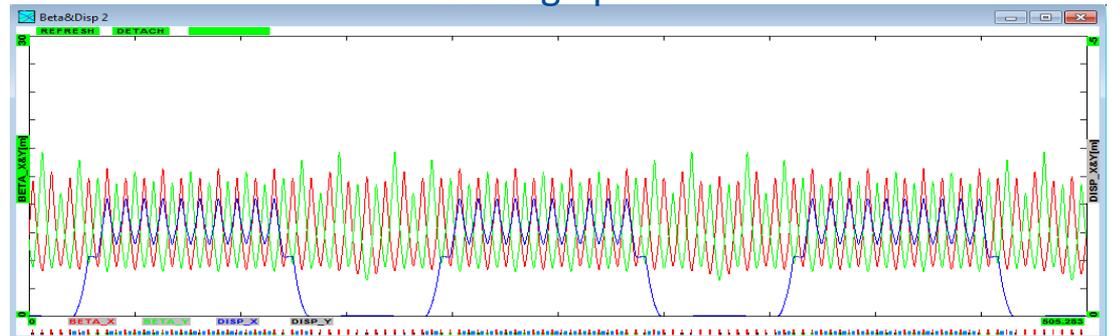


# Machine operation issues: Optics redesign

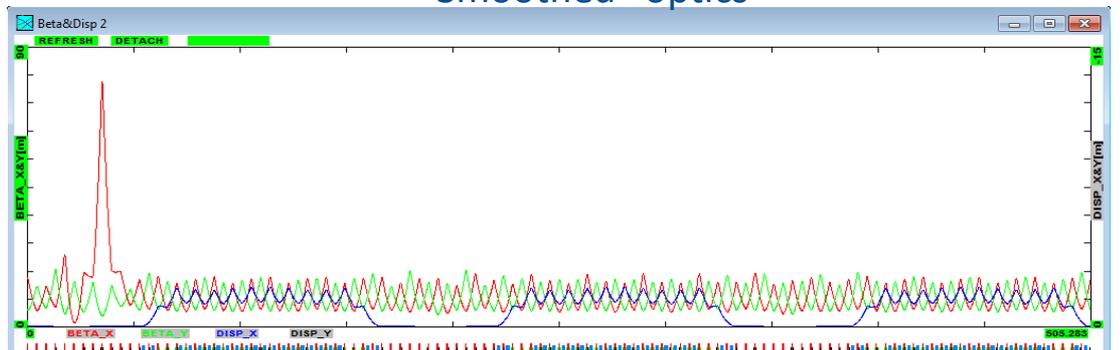
- Optics redesign
  - Smoothing optics
  - Increasing  $\beta_x$  at ESS1
- Difficulties with implementing a large beta-bump
- Currently we consider only smoothed optics design with possibly a modest beta-bump, not a part of the project baseline.



Existing optics



"Smoothed" optics

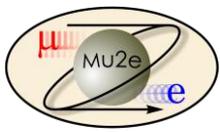


Beta-bump optics



## Magnets and Power Supplies

1. Tune ramping quads
2. Sextupole magnets
3. Dynamic (DEX) bump dipoles



# Magnets: Tune ramping quads

## Locations:

0-harmonic circuit: 3 quads in the middle of each SS. Not the only possible choice.

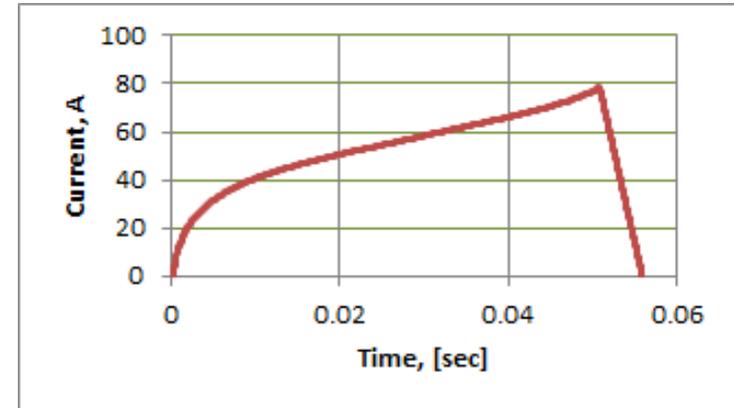
## Strengths:

$$\Delta\nu = \frac{1}{4\pi} \frac{3GL}{B\rho} \beta$$

$$GL = 0.2T$$

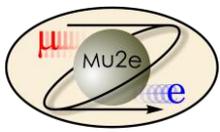
## Ramps:

The tune ramp curve was calculated from the linear spill tune curve defined in Synergia.



## Magnet and PS Specs:

- Field distortions <1%
- Stability <0.5%
- Ripple <0.05%



# Magnets: Tune ramping quads

## Choice of magnet types:

CQA type, available in storage. Air cooled.

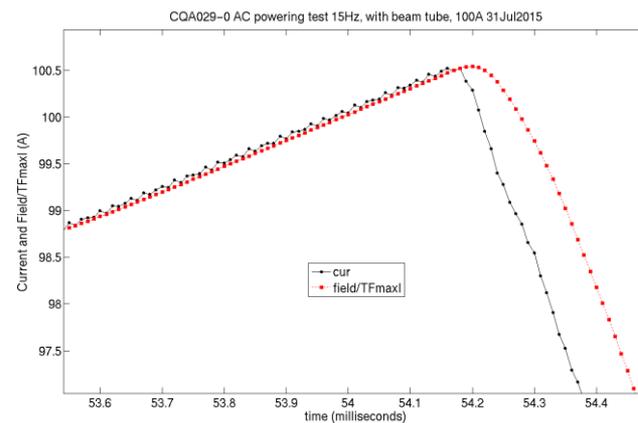
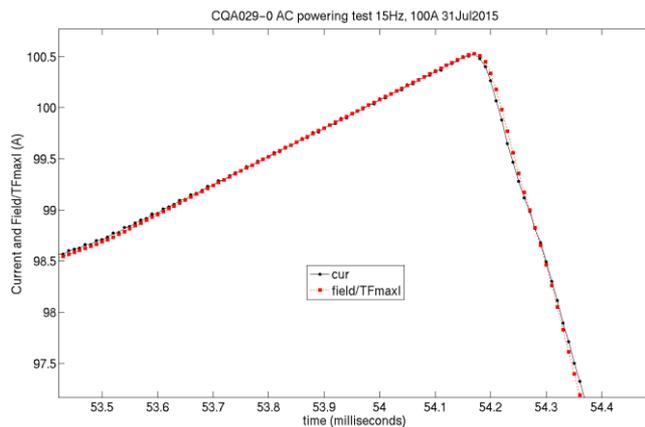
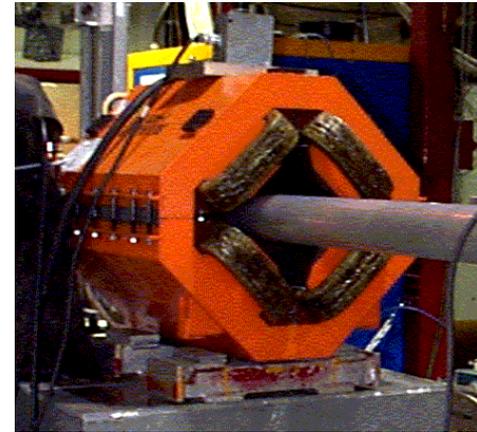
## Power supplies:

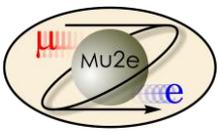
PS design is an extension of the existing Booster PS design. Low risk.

## Magnet tests performed:

Magnet performs very well on the ramp.

Field delay of  $\sim 0.1\text{ms}$  detected with SS beam pipe



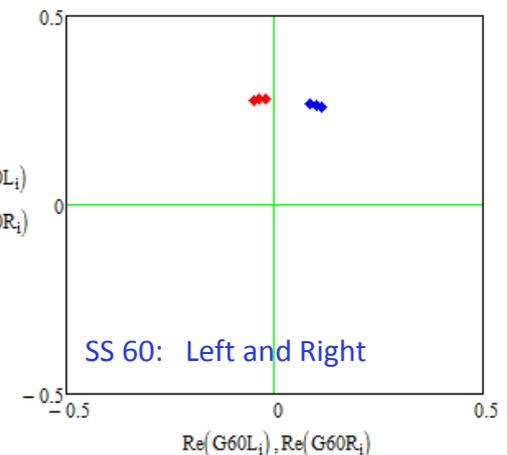
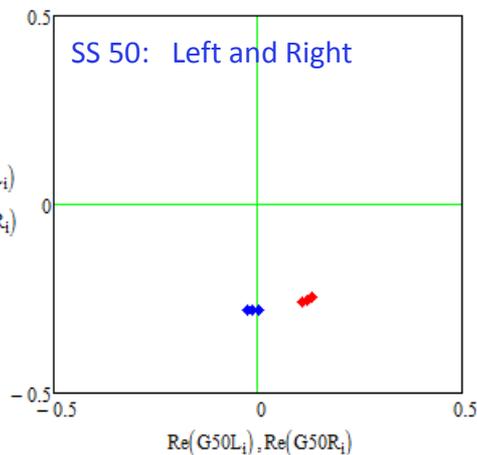
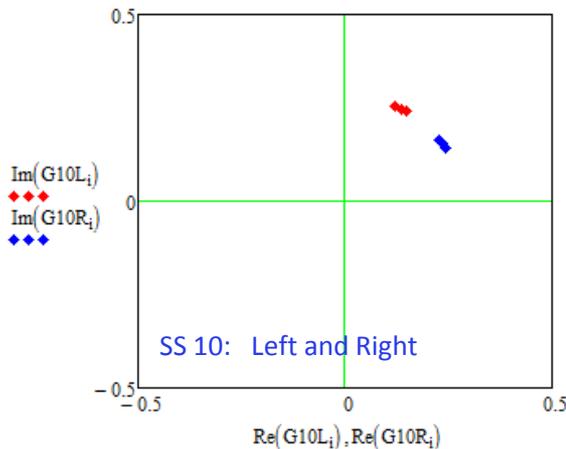


# Magnets: Sextupoles

## Strengths

$$g \approx \frac{i}{6\sqrt{2}} \frac{1}{4\pi} \sum \frac{B''L}{B\rho} \beta^{3/2} \cdot e^{-3i\psi_x} \quad \Rightarrow \quad B''L=80 \text{ T/m}$$

- Would like to have 2 orthogonal families of magnets
- FODO cell PA  $60^\circ$  is ideal for adding up
- Choice of locations available in SS50 and SS10-60
- Noticeable difference Left-Right
- Best choice: 10R+50L





# Magnets: Sextupoles

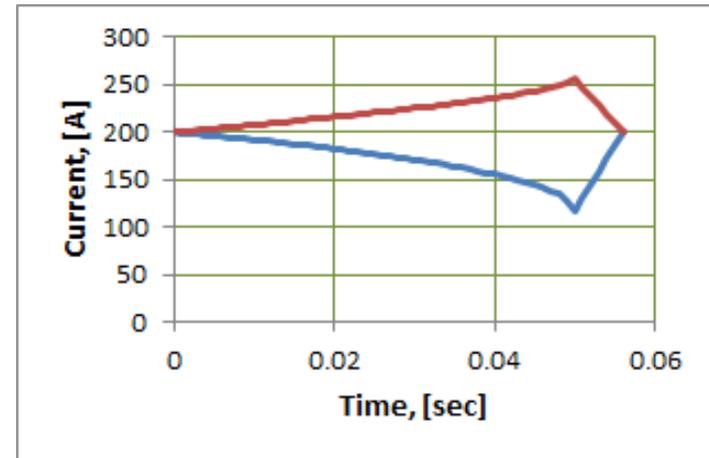
**Ramps:** There is practically no cost difference between DC and AC options. It may be useful to reserve ramping capability, e.g. to adjust separatrix orientation instead of orbit control

**Magnet choice:** Existing design of ISA magnets is suitable, but no spares – will have to build them. Water cooling is required.

**Power supplies:** PS design is an extension of the existing Booster PS design. Low risk.

## Magnet and PS Specs:

- Field distortions < 1%
- Stability < 0.5%
- Ripple < 1%





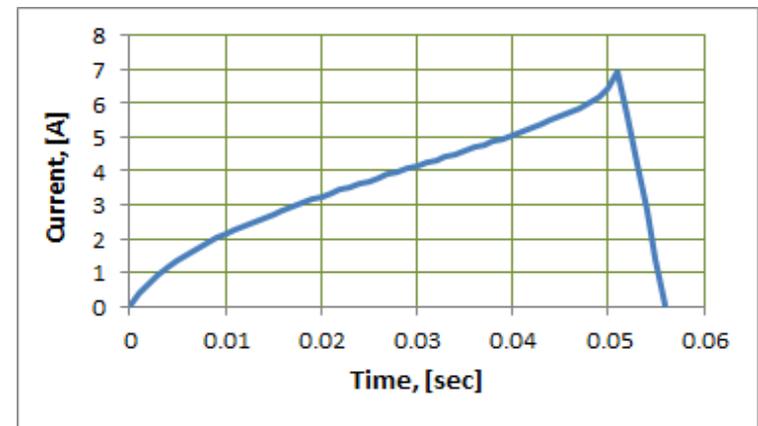
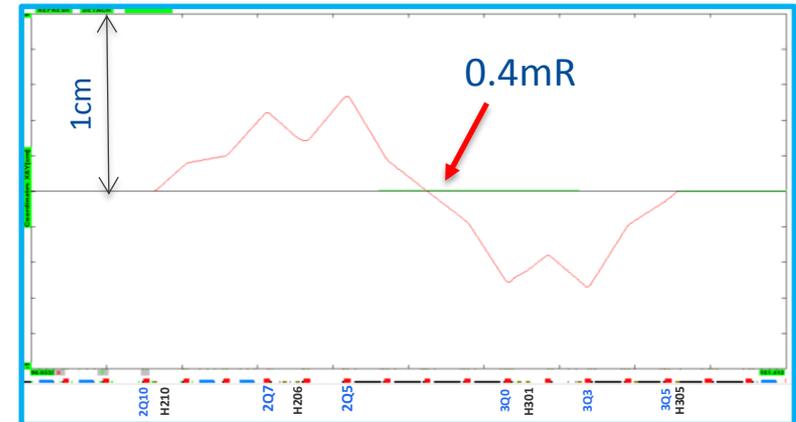
# Magnets: DEX bump

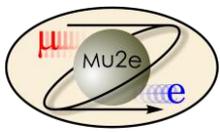
**Locations:** Very tight space in SS30 limits the choice of trim locations. Substantial orbit shifts, in particular, at Q205 is a concern.

**Kick:** 
$$\theta_{\max} = \sqrt{\frac{\varepsilon}{\gamma \cdot \beta}} = 0.4mR$$

**Strengths:** 
$$BL_{Max} = 0.014Tm$$

**Ramps:** Calculated to keep the orbit angle at ESS1 constant.





# Magnets: DEX bump

**Magnet choice:** Debuncher style NDB. Air cooling is sufficient.

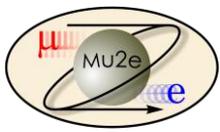
**Power supplies:** Only 7A , but needs lots of voltage to drive the fast ramp. Splitting 2 coils in parallel, augmenting the PS with the 350V regulation.

**Magnet testing:** FEA analysis show that magnet should perform well in the AC mode. However in the case of distorted lamination issues may appear, therefore testing was recommended. Tests are in progress now.



## Magnet and PS Specs:

- Field distortions < 1%
- Stability < 1%
- Ripple < 1%



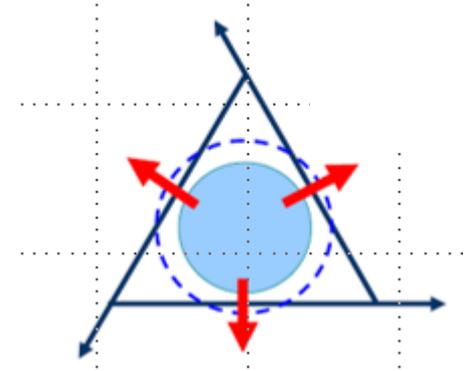
## Transverse RF Knock-Out (RFKO)

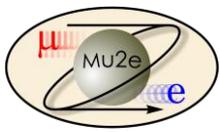
1. Overview
2. Theory and simulations
3. Measurements



# RF Knock-Out – Overview

- Transverse RFKO- fast betatron beam heating
- We will use transverse RFKO for the regulation of fast spill rate ripples.
- Simulations show that 1uR kick at max power is sufficient for fast spill regulation. (!?)
- Calculations of the emittance growth rate (EGR) are consistent with simulations and beam measurements.
- The kicker waveform has to be FM-modulated with the BW covering the beam tune spread.
- Spill regulation is made through regulating the RFKO power.
- We will use the old Tevatron damper kicker. It's already installed and tested with beam.





# RF Knock-Out – Theory and simulations

V.Nagaslaev et al., FERMILAB-CONF-11-475-A

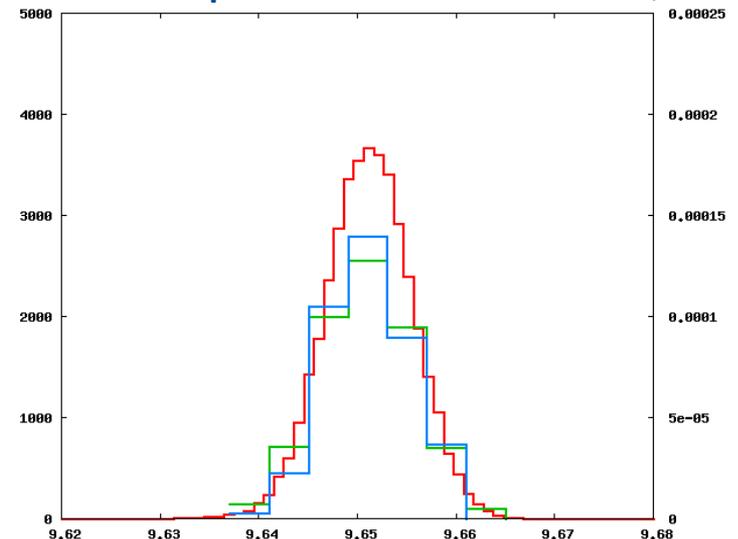
- Two types of modulation were studied in tracking simulations: linear chirp and random “colored” noise. Performance is very similar.
- Emittance growth rate (EGR) is the most essential characteristic of the RFKO heating.

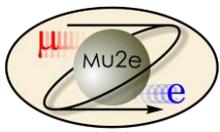
$$\frac{\Delta\epsilon_{95}}{\Delta t} = \frac{3\theta_0^2 \beta_x}{4\Delta Q} \cdot f_0 \cdot F(Q, \Delta Q)$$

Tune distribution and emittance growth rates in narrow BW:

- proportional to occupancy
- close performance

Beam tune spread and EGR in narrow  $\Delta Q$  bins





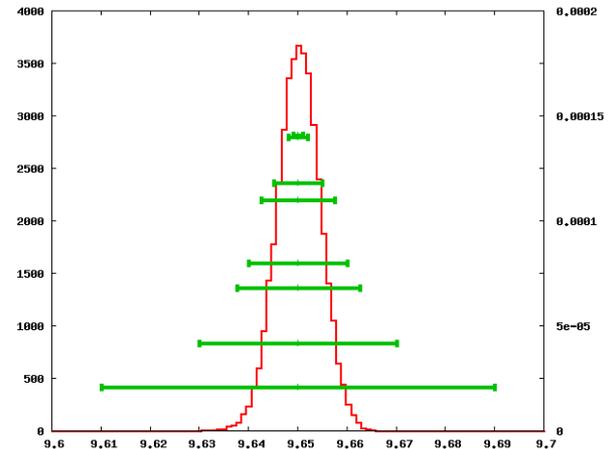
# RF Knock-Out – Theory and simulations

$$\frac{\Delta\varepsilon_{95}}{\Delta t} = \frac{3\theta_0^2 \beta_x}{4\Delta Q} \cdot f_0 \cdot F(\Delta Q)$$

Tune distribution and emittance growth rates with wide BW:

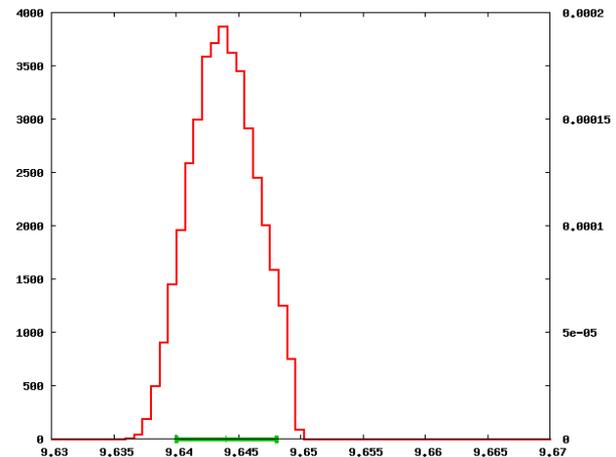
- $\sim 1/\text{width}$

Beam tune spread and EGR in wide  $\Delta Q$  bins



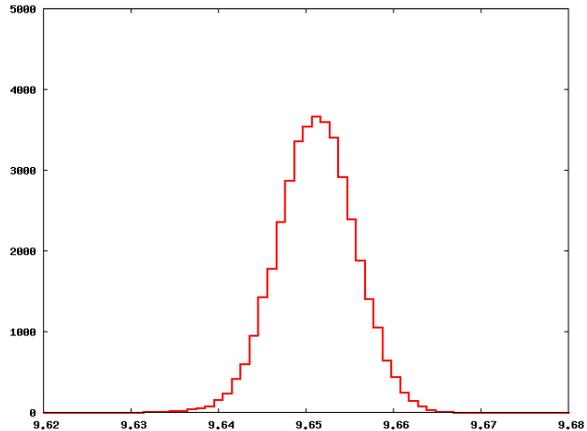
What if the tune width is dominated by the Space Charge?

Tune width due to the SC alone does not provide any mixing, so EGR=0

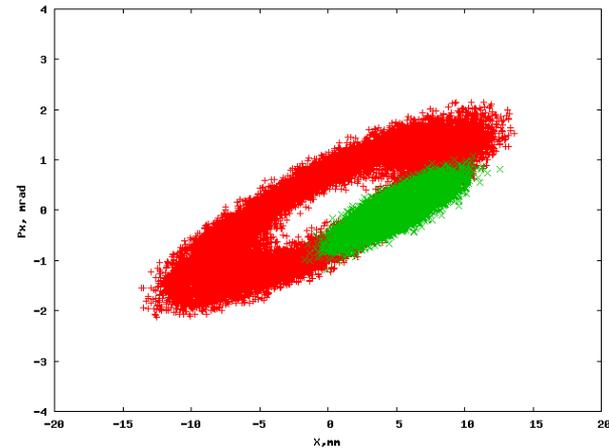




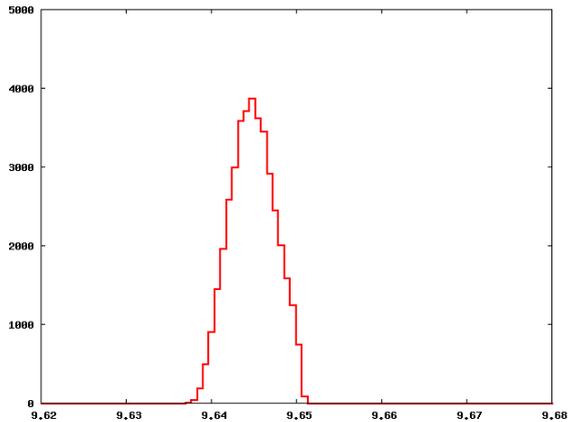
# RF Knock-Out – Theory and simulations



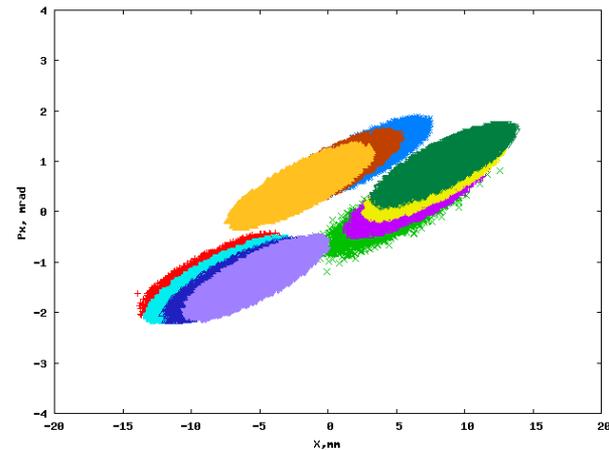
$C_x=2$ ; SC is off



Phase space after 1000 turns



$C_x=0$ ; SC is on Phase space after EACH of 1000 turns





# RF Knock-Out – Comparing with measurements

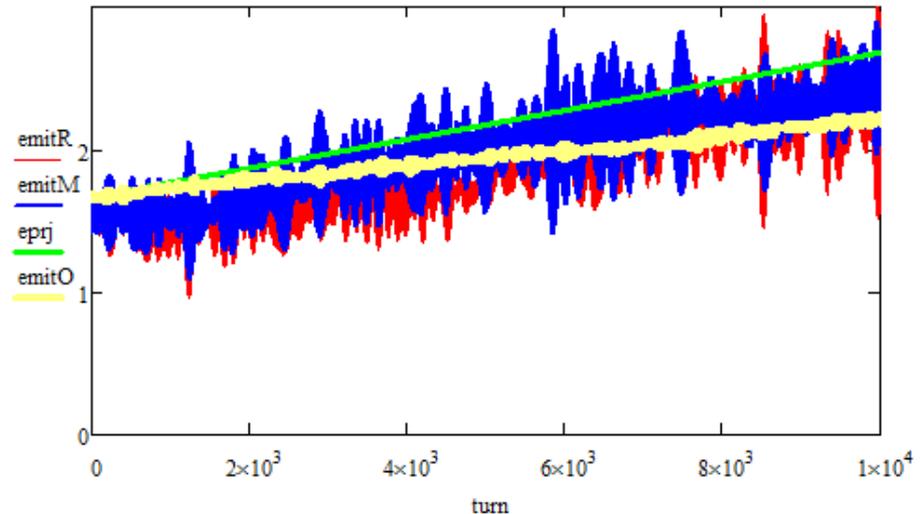
$$\frac{\Delta \epsilon_{95}}{\Delta t} = \frac{3\theta_0^2 \beta_x}{4\Delta Q} \cdot f_0$$



**$60\pi$  mm-mr/sec**

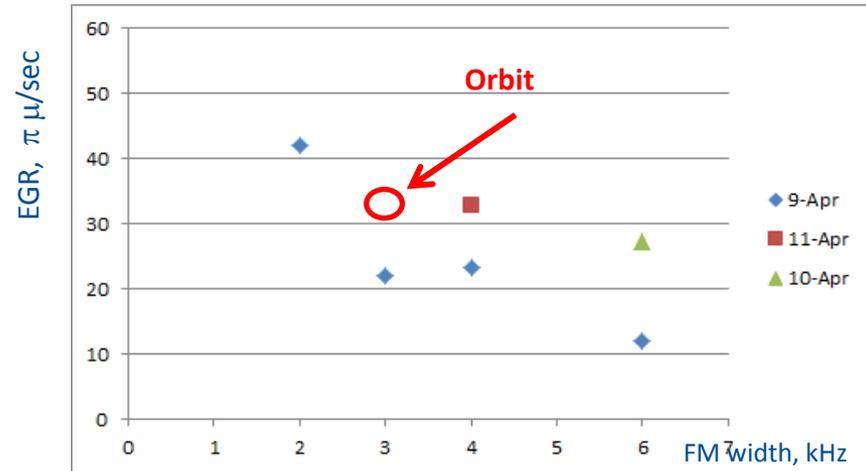
**EGR(Orbit) =  $33\pi$  mm-mr/sec**

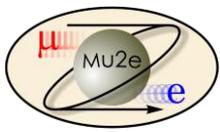
@ 25W+25W



EGR measurement in the  
Debuncher ring:

- Difficult measurements
- Final results consistent with calculations





# RFKO Summary

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1. RFKO emittance growth is inversely proportional to the beam tune spread
2. RFKO needs non-zero chromaticity and chromatic tune spread
3. Chromatic tune spread should be large enough to ensure fast mixing
4. Calculated emittance growth rates are consistent with simulations and beam measurements

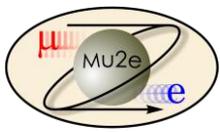


# Spill Control

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## Spill Control

1. Simulations
2. Regulation logic
3. Spill Monitoring

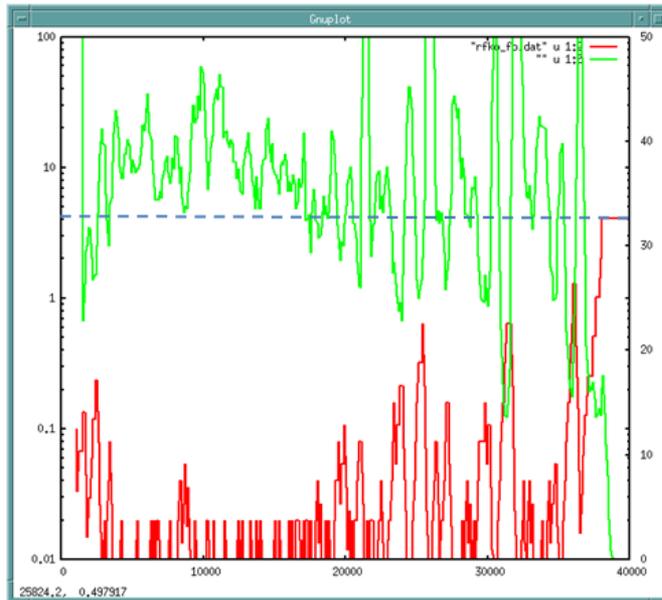


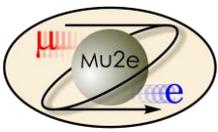
# Spill Control system

- Required: spill uniformity at the level of  $\pm 50\%$
- On average spill is controlled by the tune ramping quad circuit
- We plan to regulate fast spill variations with the RFKO kicker
- RFKO is fast and proved to be very effective in slow extraction for medical applications
- We are cautiously optimistic about use of.

## Early simulations of the RFKO regulation with ORBIT:

- No regulation when spill rate is high
- Large variations
- High statistical noise

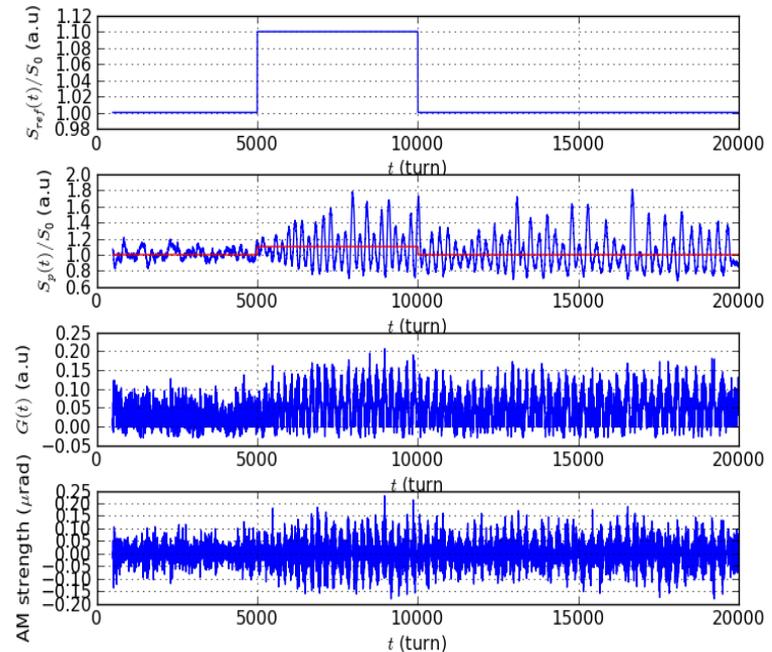




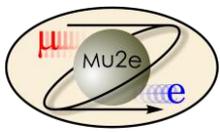
# Spill Control system

## RFKO regulation simulations with Synergia:

- Regulation responds to 10% increase in the reference spill rate
- Large variations
- High statistical noise



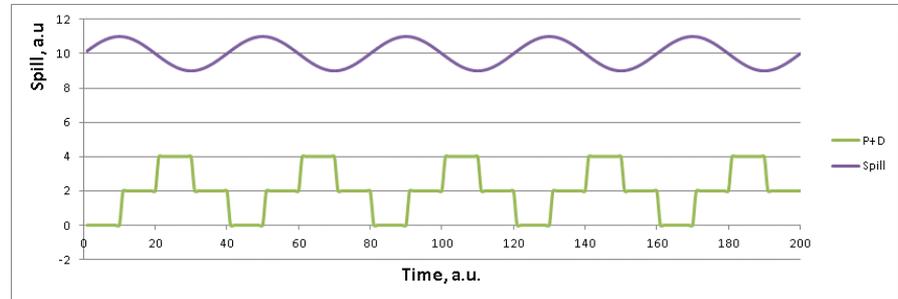
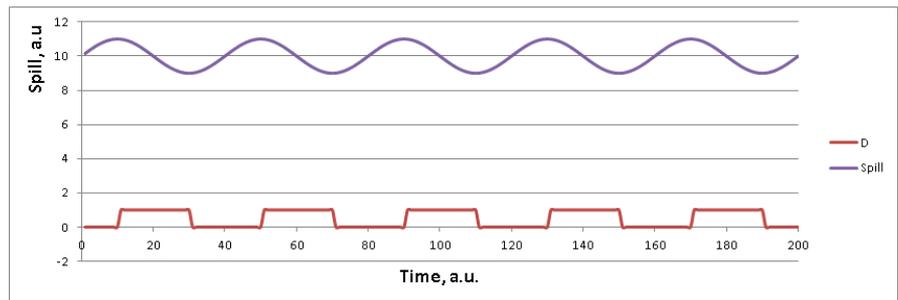
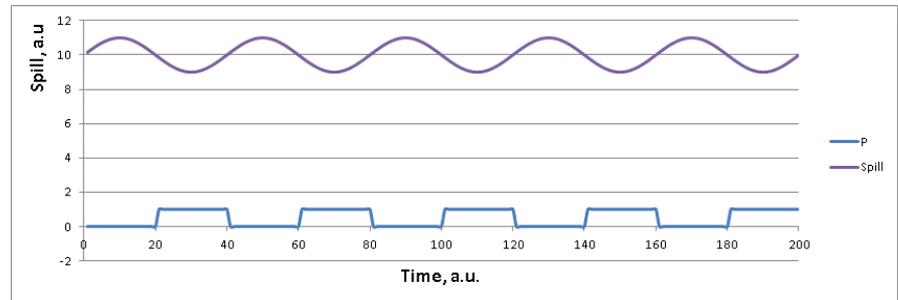
Proportional regulation seems to do the job, but it produces large oscillations due to the beam response latency and overregulation

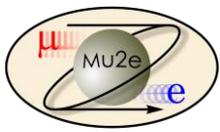


# Spill Control system: overregulation

- Oscillations in the spill rate appear as a result of beam response latency and overregulation with proportional loop P
- This can be alleviated by using the derivative regulation loop D
- Or a combination of P and D

Derivative loop has a “prediction” power and therefore has a potential to smoothen oscillations. Problem of tracking simulations is that D signal is intrinsically very noisy. Same problem may occur if the SM sensitivity is limited.





# Spill Control system: noise-free simulations

For practical purposes of the electronics FB simulations we developed a simplified NOISE-FREE semi-analytical model of RE:

- Beam distribution is assumed to have a Gaussian shape limited by the separatrix size  $A(t)$ :

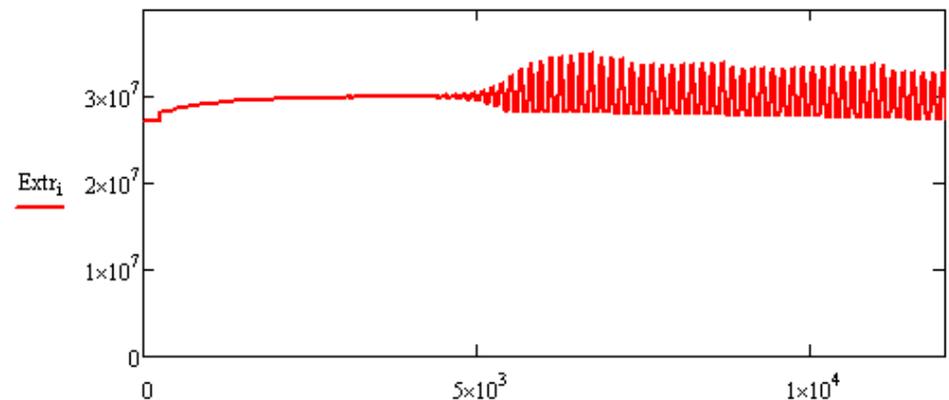
$$P(I) = \frac{1}{I_0} \exp\left(-\frac{I}{I_0}\right) \quad \leftarrow I < A(t)$$

$$P(I) = 0 \quad \leftarrow I > A(t)$$

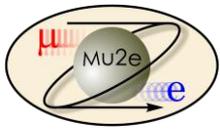
$$I_0 = 2\varepsilon_x$$

- On each step recalculate:
  - New  $\varepsilon_x$
  - New  $A(t)$
  - New part of beam outside of the separatrix
  - New extracted beam
  - Spill Monitor response
  - Spill error signal
  - Regulation gain
  - RFKO power

The model is now employed for the hardware optimizations

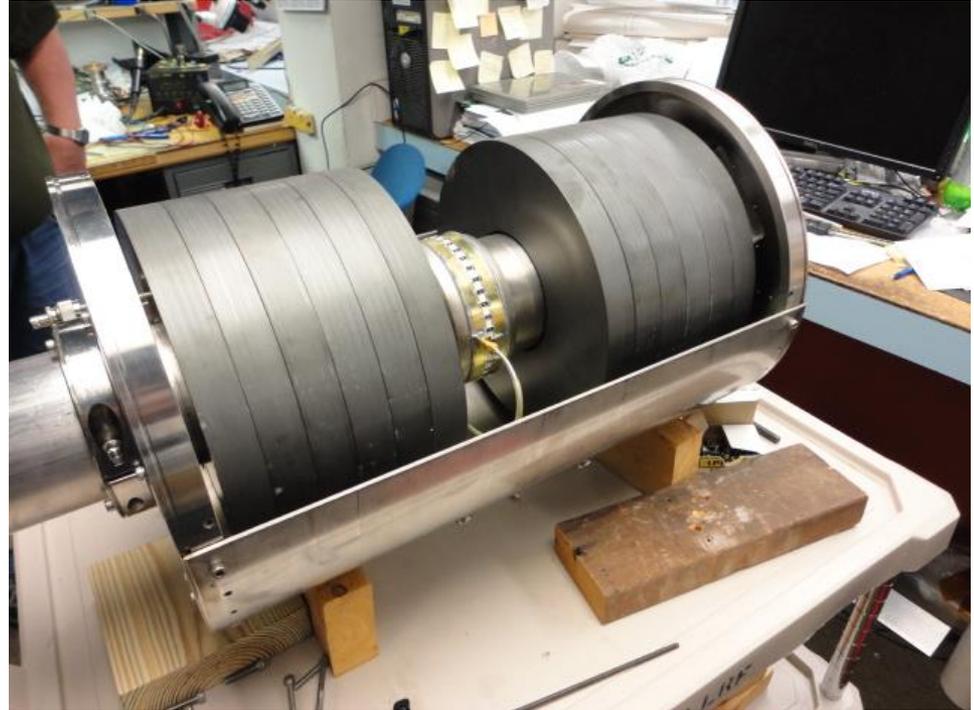


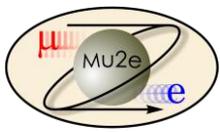




# Spill Monitoring

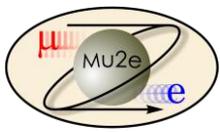
- Dedicated WCM device for SM
  - Enhanced sensitivity
  - Beam tested
  - Ready for use
- Will use DR DCCT for additional I-loop input
- Will need additional instrument for the D-loop input. Plan to use the Extinction Monitor output.





## Electrostatic Septum Design

1. Design considerations
2. Beam losses budget
3. Prototyping
4. Full scale prototype



# ESS design considerations: foils

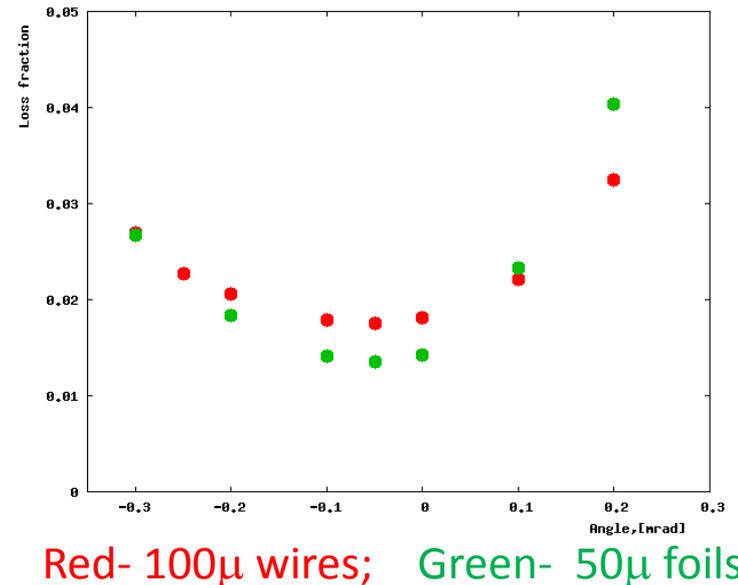
## Foils or wires?

MARS:

- ✓ 100 $\mu$  dia wires; 50 $\mu$  foils
- ✓ Conservative case
- ✓ Narrow angle spread beam
- ✓ No significant advantage

- Would the foils stay flat?
- Would a wire be destroyed by a single spark?

Total losses vs beam angle.



Red- 100 $\mu$  wires; Green- 50 $\mu$  foils

The choice does not appear to be obvious, but at this point we prefer foils as a more mechanically stable option



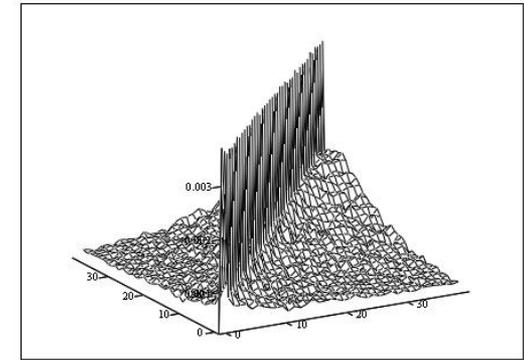
# ESS design considerations: pre-scattering

## Do we need a diffuser?

- ✓ Losses predominantly occur for those particles that pass through the septum plane at low angle
- ✓ These particles can be deflected to a small angle by the diffuser plane in front of the septum plane
- ✓ Works best with low density materials (e.g. Carbon)
- ✓ Mo foil plane can also be effective with foil spacing of 20mm

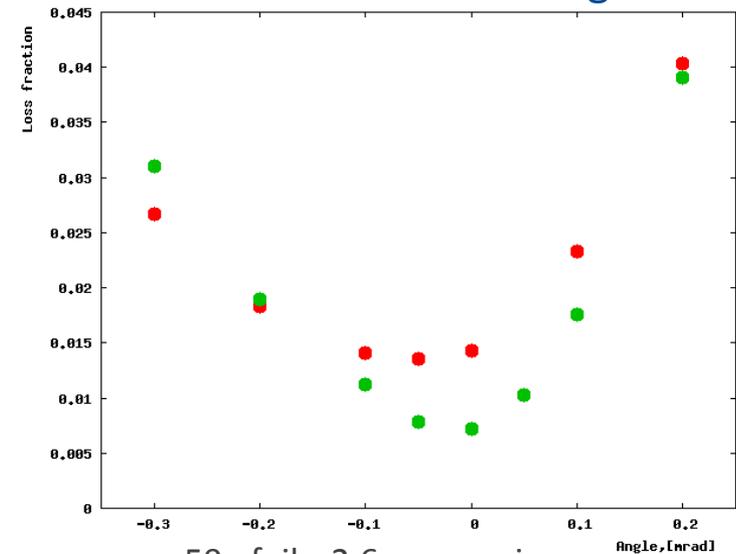
We reserve 0.5m of frame length in front of the foil plane of ESS1 for the diffuser.

Optimal geometry for the diffuser

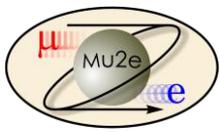


D

## Total losses vs beam angle.



Green— with diffuser; Red — without diffuser

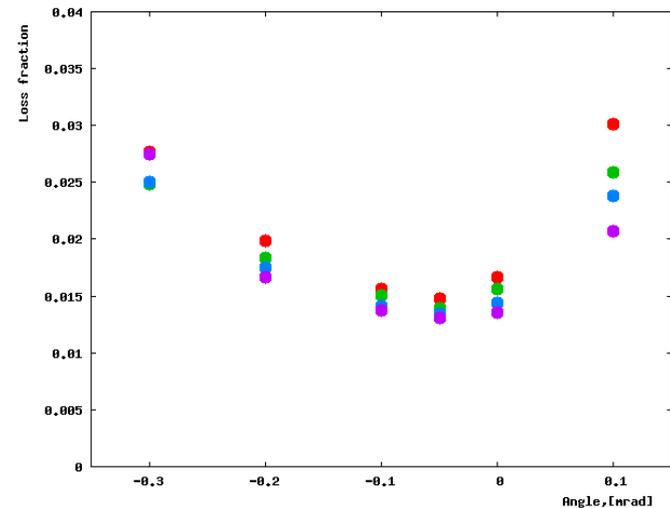


# ESS design considerations: septa lengths

## What's the optimum ESS length ratio?

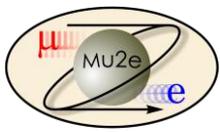
- ✓ Losses are most significant in ESS1
- ✓ Losses grow with ESS1 length due to the beam angle spread
- ✓ Performance can be improved by making  $L1 < L2$

MARS:  
Total losses vs beam angle.

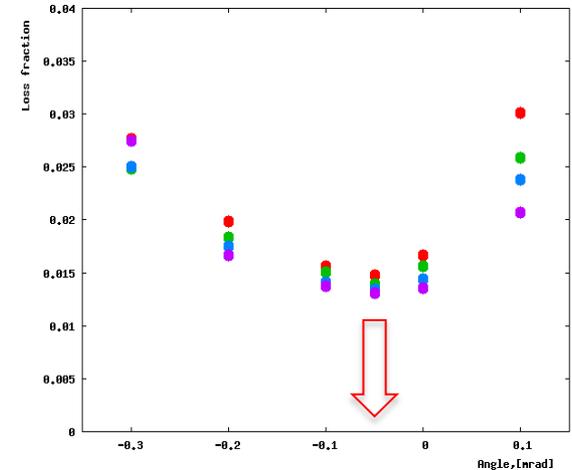
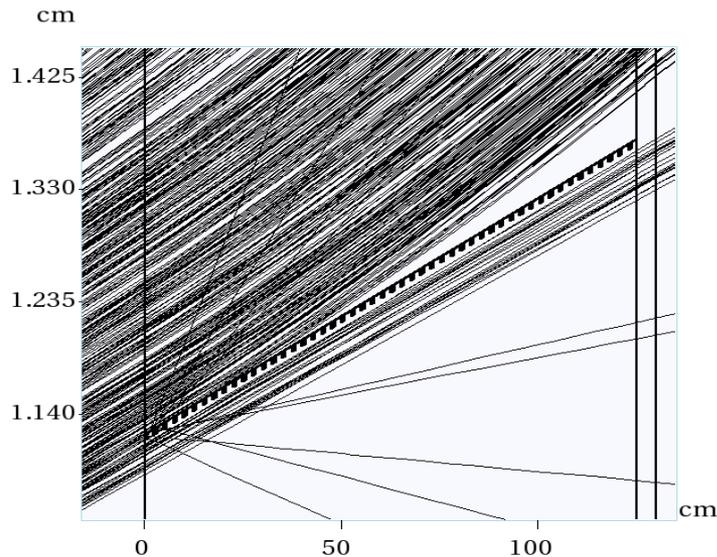


ESS1/ESS2 length ratio:  
Purple-0.5m/2.5m; Blue-0.7m/2.3m; Green-1m/2m; Red-1.5m/1.5m

Practical choice:  $L1=1.25\text{m}$  (+0.5m diffuser) and  $L2=1.75\text{m}$  leads to equal total vessel lengths. This makes design of two septa fully interchangeable.

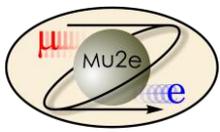


# ESS alignment and flatness



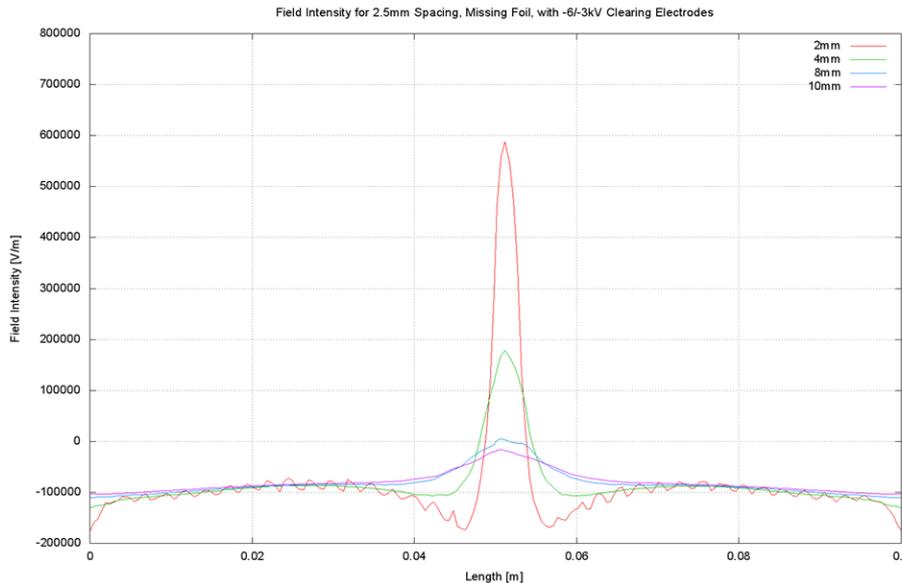
- Optimal ESS alignment angle
- Losses sensitive to misalignment or wide angle spread
- Flatness is most important in first part of ESS1
- Small positive bend acceptable in the end of ESS1

- Design should allow flipping the frames
- It might be beneficial to introduce a small positive bend in the end of ESS1
- Motion control better than 50u



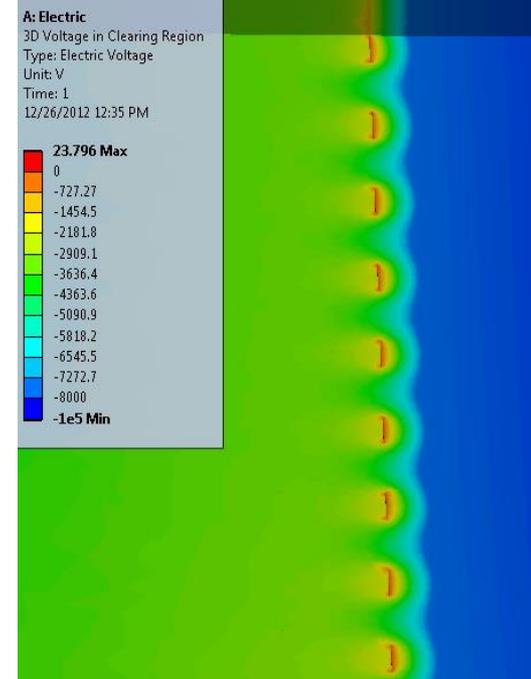
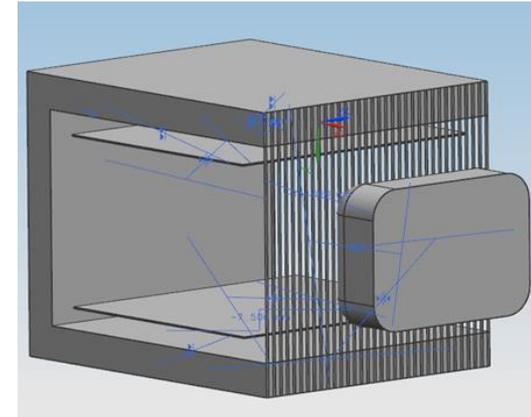
# ESS design considerations: ions

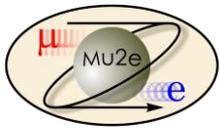
## How to minimize effect of ions?



It is believed that if ions created in residual gas are pulled into the strong field gap, they assist spark generation. Field penetration from the ESS gap into the area of high density proton beam should be avoided even if there is a broken foil.

Clearing electrodes required (up to 10kV)  
Allowed spacing = **2.6 mm** center-center



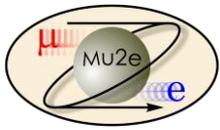


# ESS Design studies overview

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## Need to do the engineering studies:

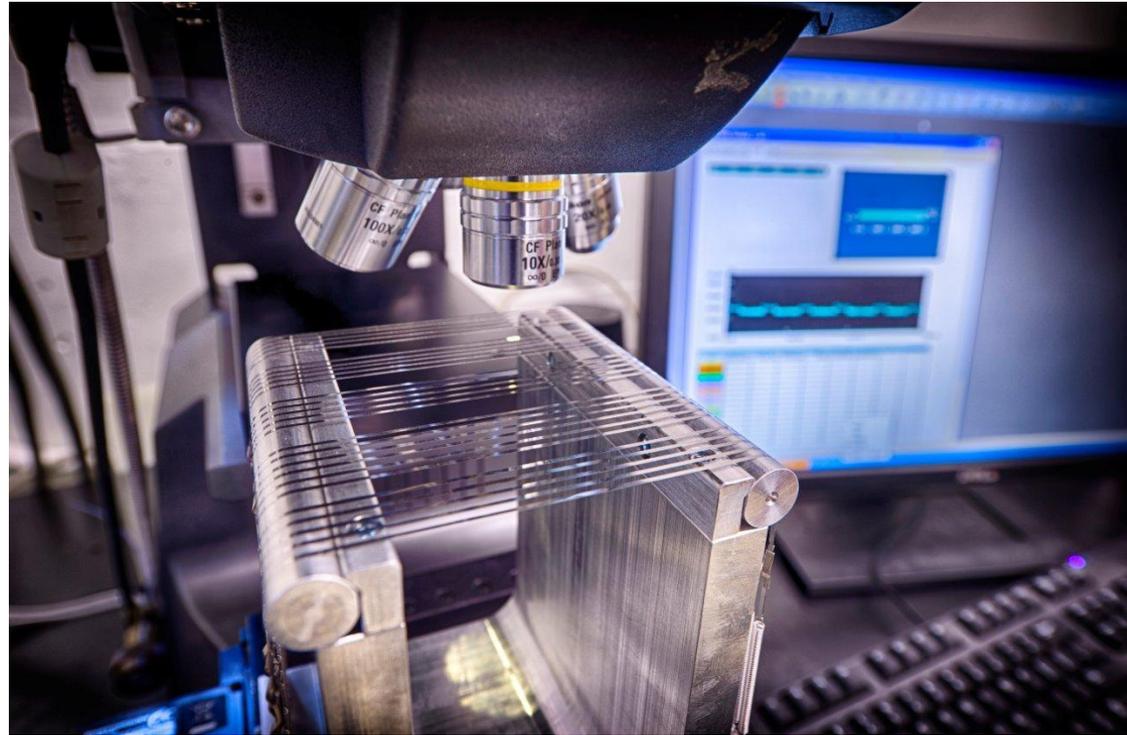
- Foil strength, yield
- Attaching foils: crimping, brazing
- Foil stretching, removal, assembly
- Foil flatness
- High voltage studies

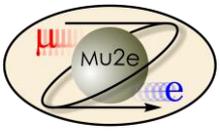


# ESS prototyping

## “Prototype-1”

- Foil attachment
- Stretching
- Test flatness
- Completed

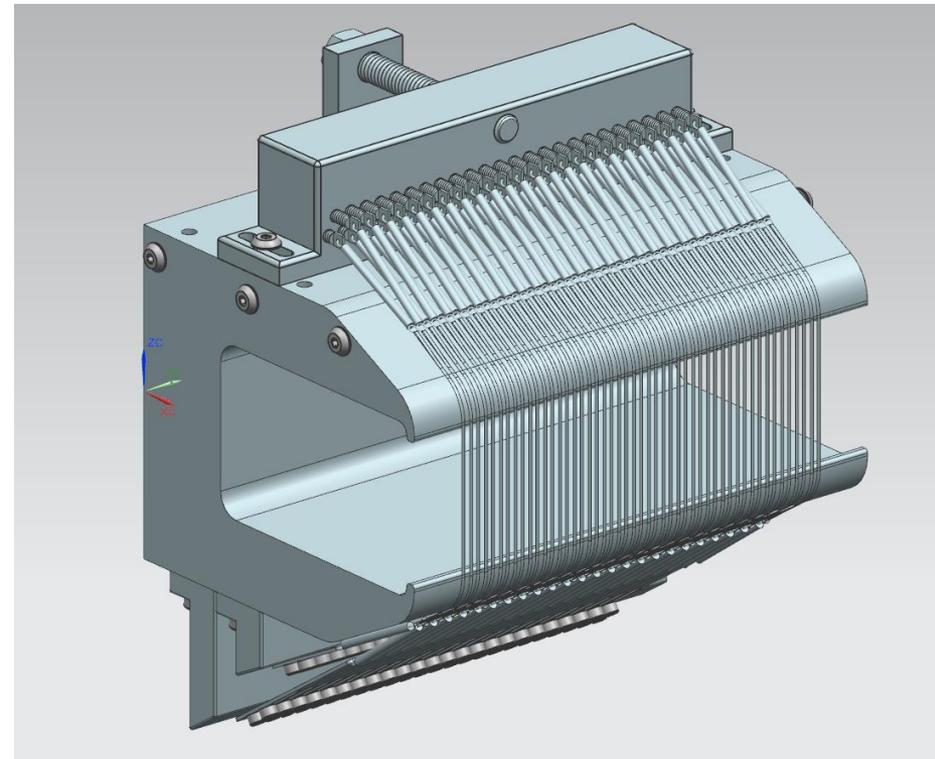


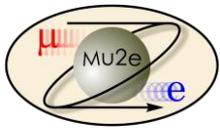


# ESS prototyping

## Stretching prototype

- Foil attachment
- Foil assembly techniques
- Test flatness
- In progress
- *See presentation of M.Alvarez*



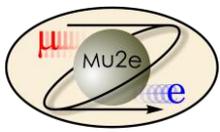


# ESS prototyping

## HV Prototype

Vacuum facility- NWA

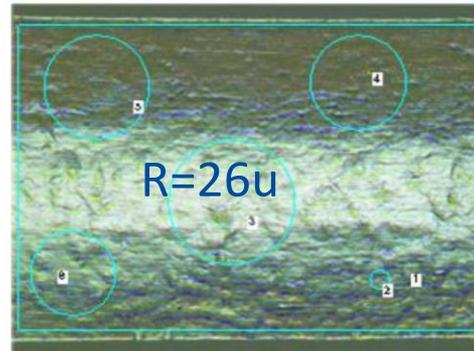
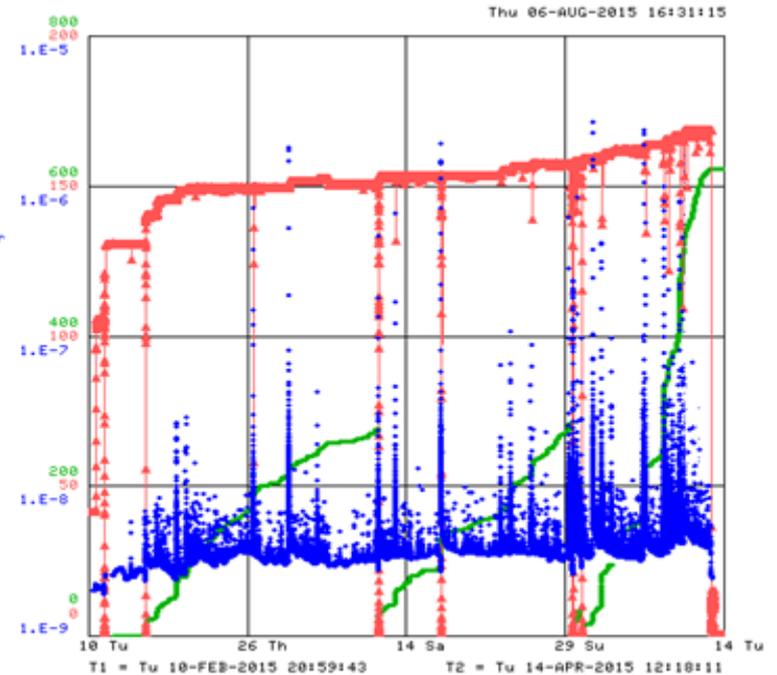


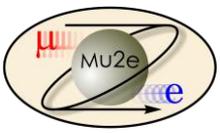


# ESS prototyping

## HV Prototype

- Foil breaking limit
- Cathode material, handling
- Feedthrough
- Foil materials
- Conditioning techniques
- Period of extremely hard conditions
- Lots of interesting observations
- In progress
- *See presentation of M.Alvarez*

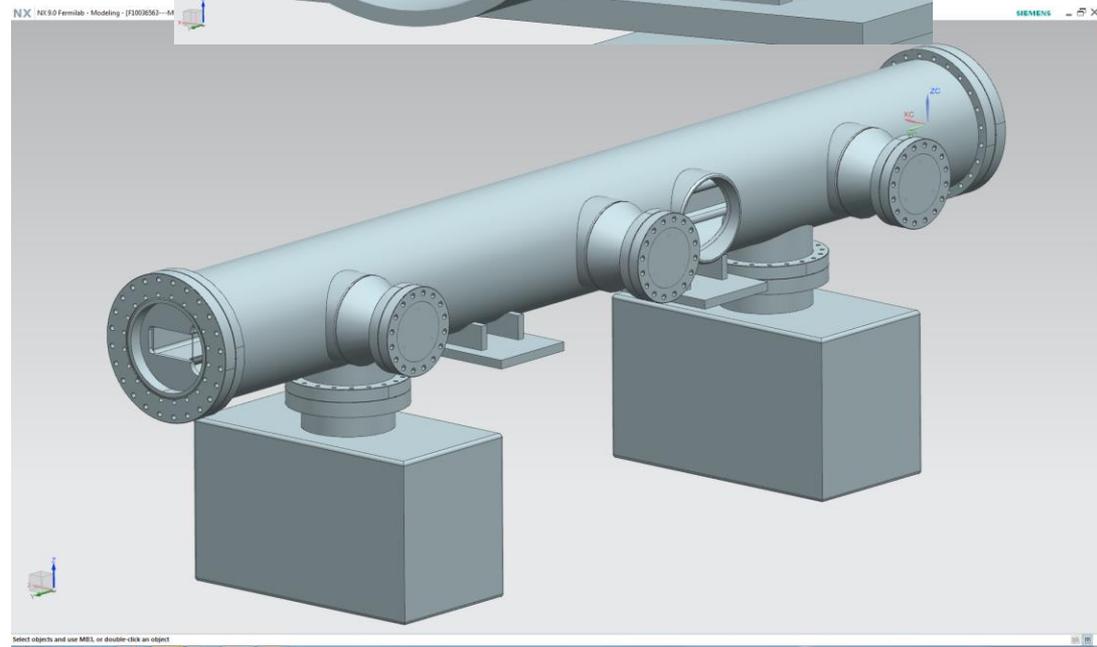
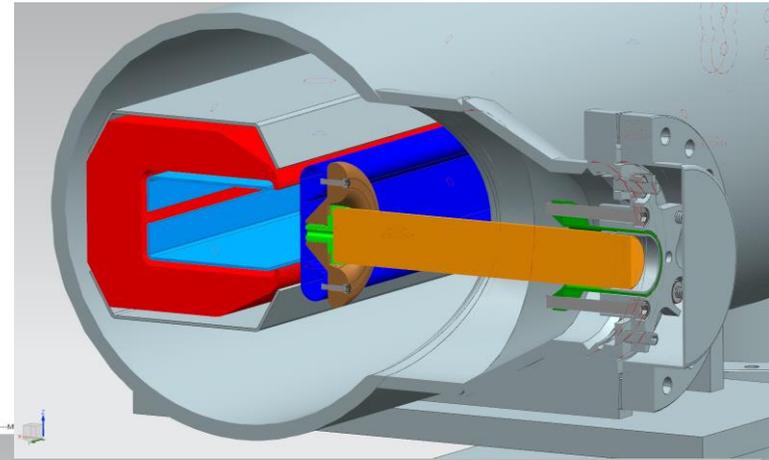


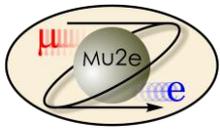


# ESS prototyping

## Large scale prototype

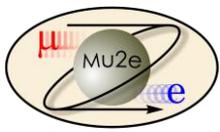
- Working towards the full scale prototype
- Test design solutions in real scale
- Satisfy ESS specifications
- Preproduction prototype
- May reuse parts in production
- *See presentation of D.Tinsley's*





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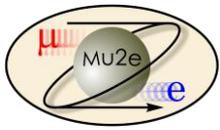
# Conclusions



# Conclusions

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- The physics model of slow extraction has been developed to determine the key system parameters and hardware specs
- We have a plan of building the new hardware and a plan to ensure the performance parameters will be met.
- Material and design studies for the ESS with the foil plane are in progress and we proceed with the full scale preproduction prototype.
- Technical and operational risks are being addressed and in most cases mitigated.

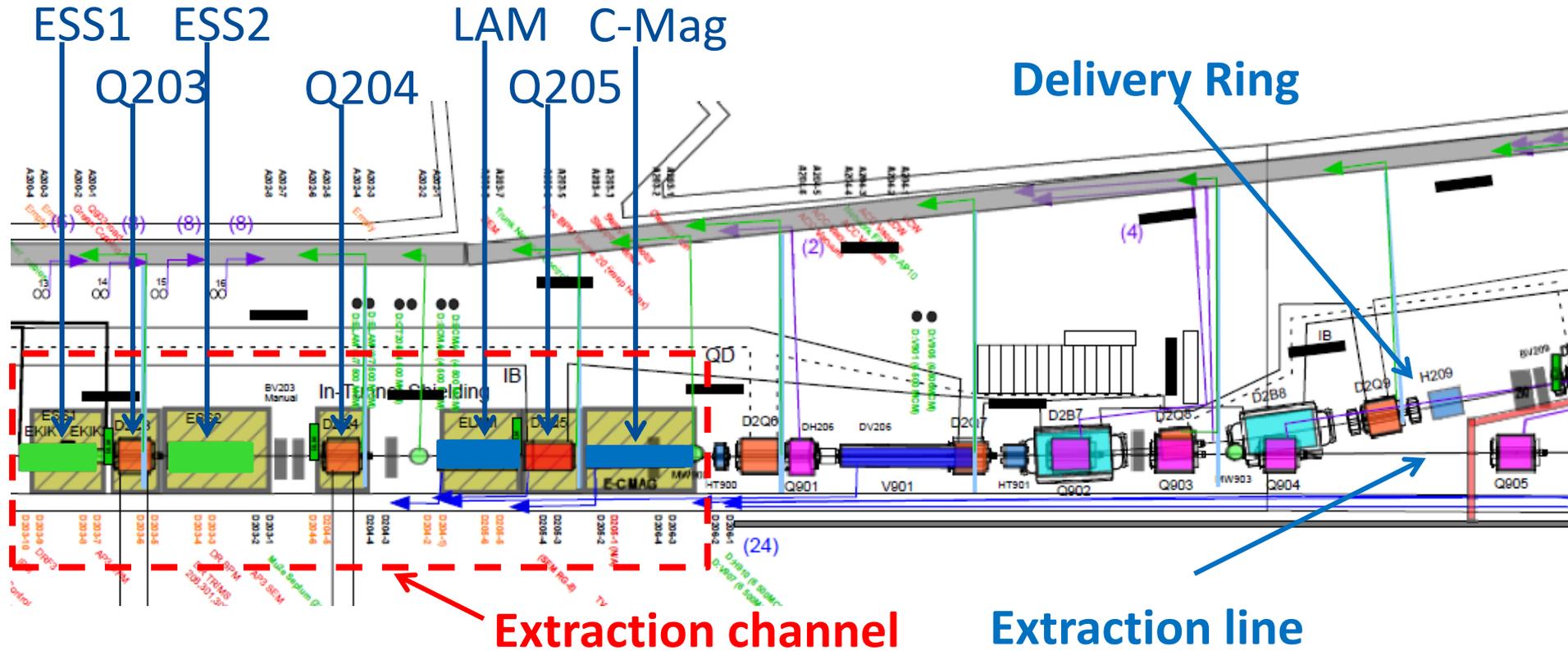


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# Supplemental slides

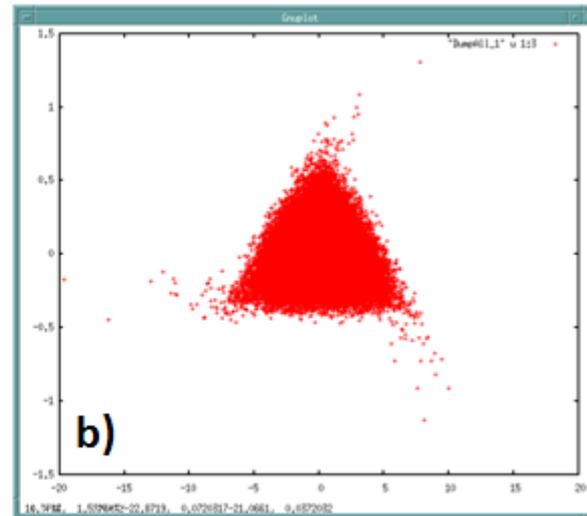
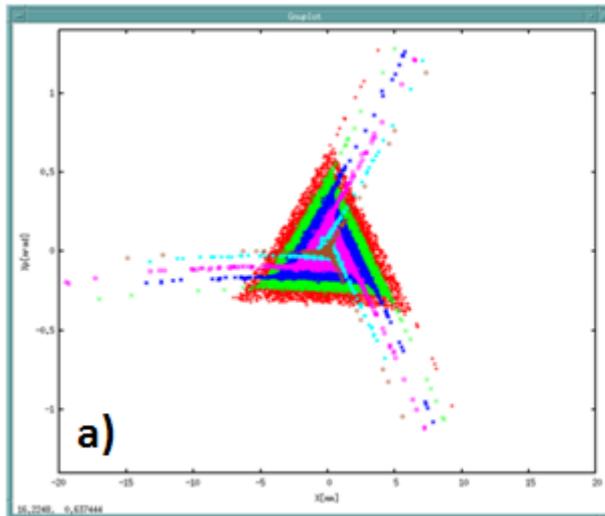


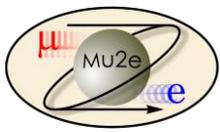
# Extraction channel



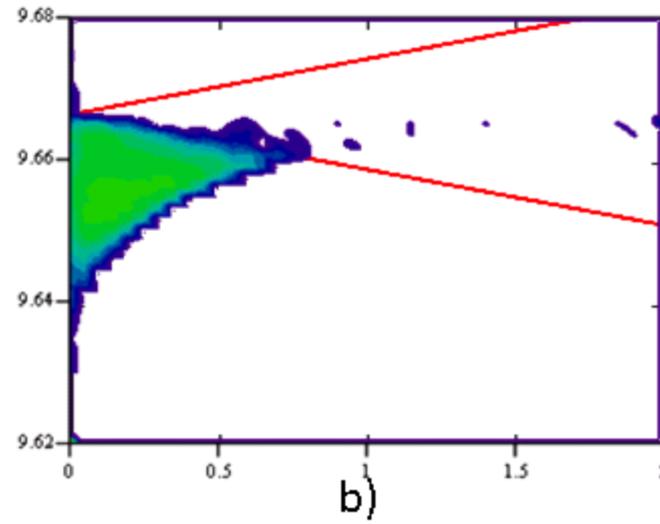
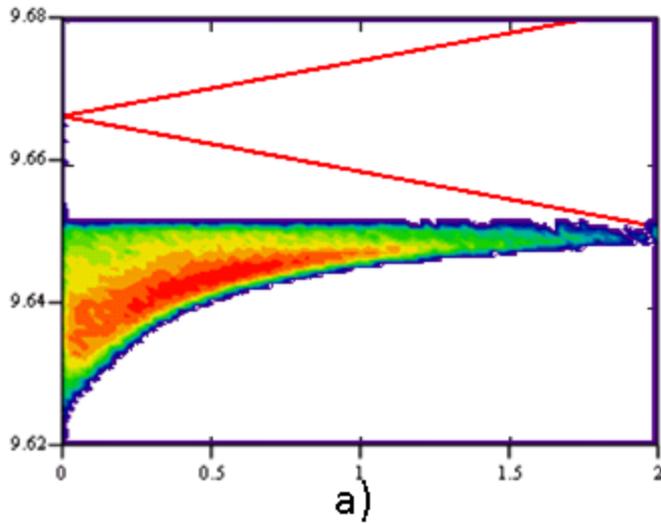


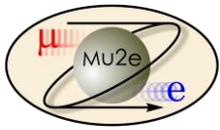
# Extracting from multiple separatrices





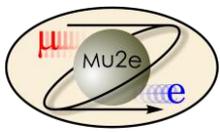
# Approaching resonance with SC





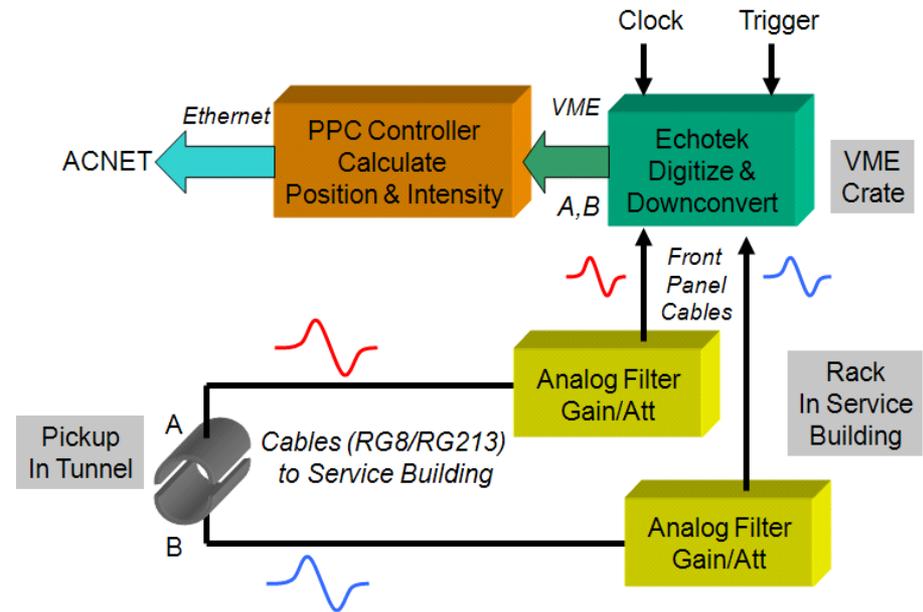
## Special Topics

1. Instrumentation
2. Technical risks
3. Radiation protection
4. Machine protection

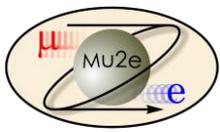


# Instrumentation: BPMs

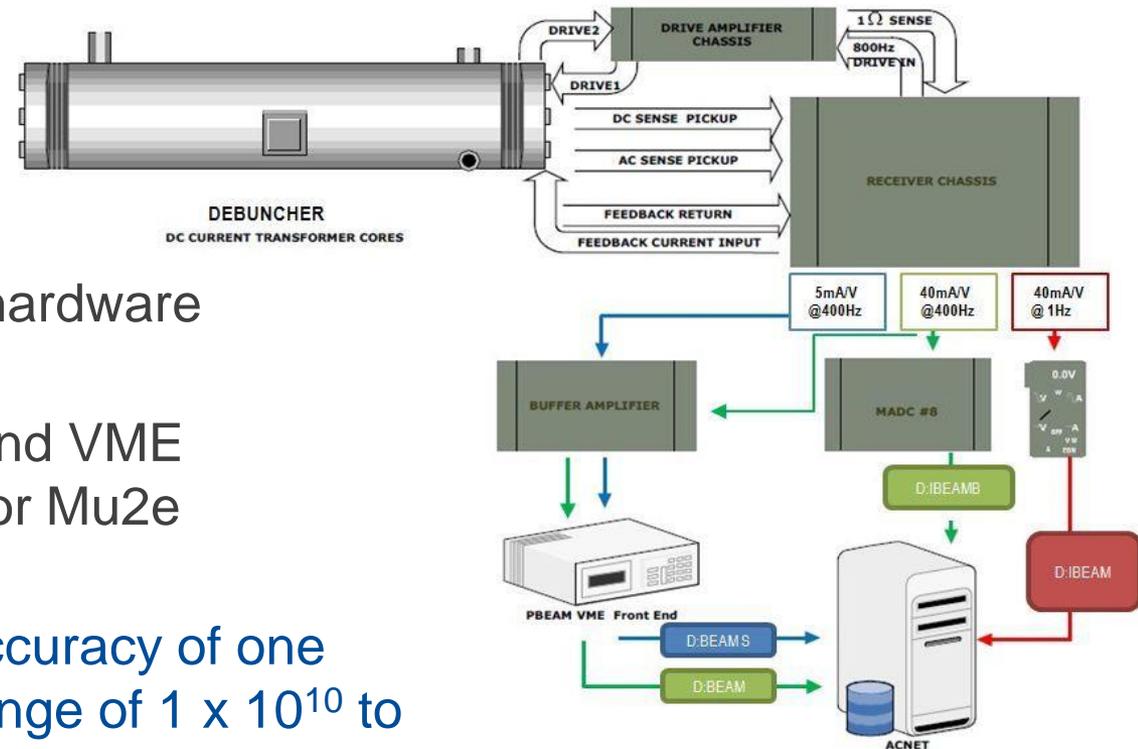
- Debuncher BPMs can only see 53MHz and will be upgraded to Echotech standard with 2.5MHz electronics.
  - Repurpose Tevatron BPM crates
  - Repurpose Recycler BPM electronics
- Tunnel hardware will be repurposed.
- BPMs will have sub-millimeter resolution.
  - Closed orbit and TBT available.
- Delivery Ring BPM system is off-project on the Delivery Ring AIP.



Courtesy B.Drendel



# Instrumentation: DCCT



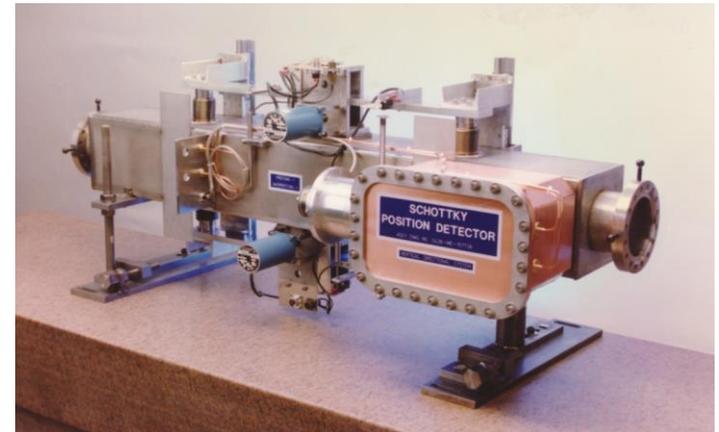
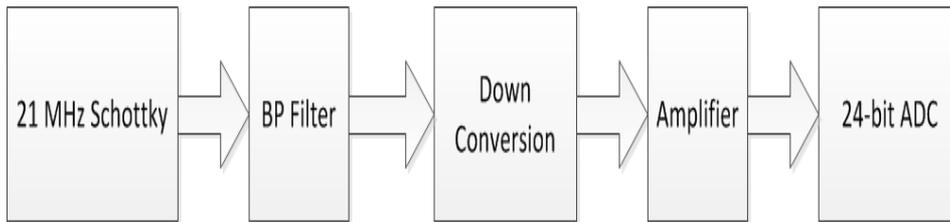
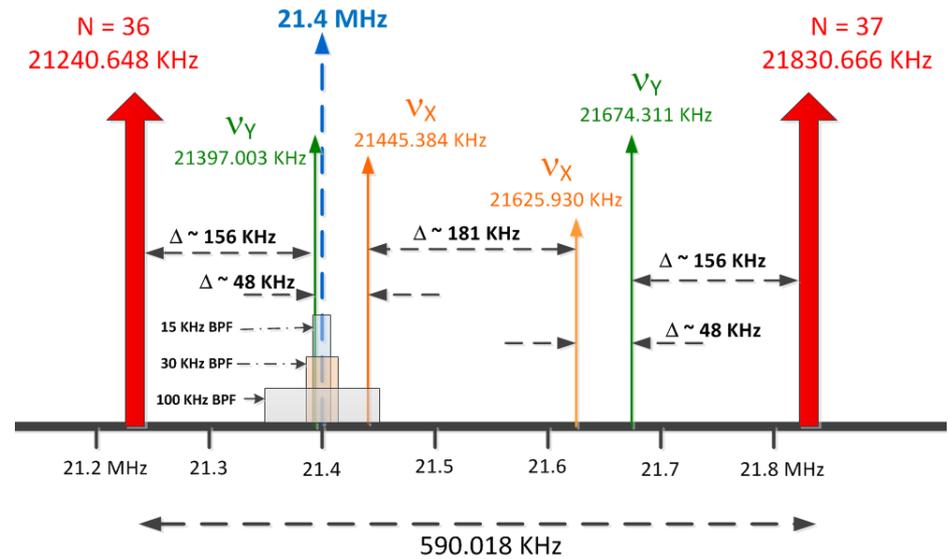
- Delivery Ring DCCT hardware repurposed.
- Analog conditioning and VME electronics modified for Mu2e operation.
- The system has an accuracy of one part in  $10^5$  over the range of  $1 \times 10^{10}$  to  $2 \times 10^{12}$  particles with a noise floor of  $2 \times 10^9$ .
- The Accumulator unit will become a working spare.

*Courtesy B.Drendel*

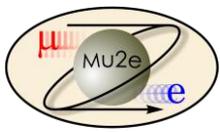


# Instrumentation: Schottky

- Repurpose Tevatron 21.4MHz Schottky which has an acceptable aperture.
- Down convert from 36<sup>th</sup>/37<sup>th</sup> harmonics to 1<sup>st</sup> harmonic (0 to 590 KHz)
- Use 24-bit ADC to sample signal
  - 2 to 4 MHz sampling
  - 100 db dynamic range
- Use digital signal processing to produce tunes
  - Tunes to  $\pm 0.001$  at 590 Hz
  - Tunes to  $\pm 0.0001$  with averaging over many spills



Courtesy B.Drendel

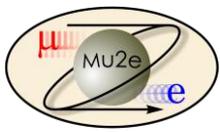


# Instrumentation: BLMs



- The M4 Line Beam Loss Monitor (BLM) system has been designed to measure a 0.2% localized loss with microsecond integration.
- This will allow seeing losses develop inside of an individual slow spill.
- 30 BLMs will be placed at key locations along the 245m beam line.
- This system design is identical to the existing Main Injector, P1, P2, M1 and M3 line BLM systems.
- There is not a sufficient pool of spare hardware and electronics so new parts will need to be purchased and constructed to build the system.

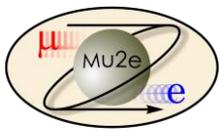
*Courtesy B.Drendel*



# Technical risks

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1. Technical Risks (extraction specific)
  - a. High losses
    - Large effective thickness of ESS planes
    - Insufficient kick in the ESS
    - Inadequate ESS alignment
    - Inadequate orbit control
  - b. High spill variations
    - Regulation is not fast enough
    - Regulation is not deep enough
    - Insufficient RFKO power
  - d. Insufficient aperture
  - e. Magnet strengths are not sufficient
  - f. Magnet ramping capabilities are insufficient
  - g. Insufficient machine diagnostics
  - h. Substantial fraction of the beam not extracted
  - i. Beam instabilities

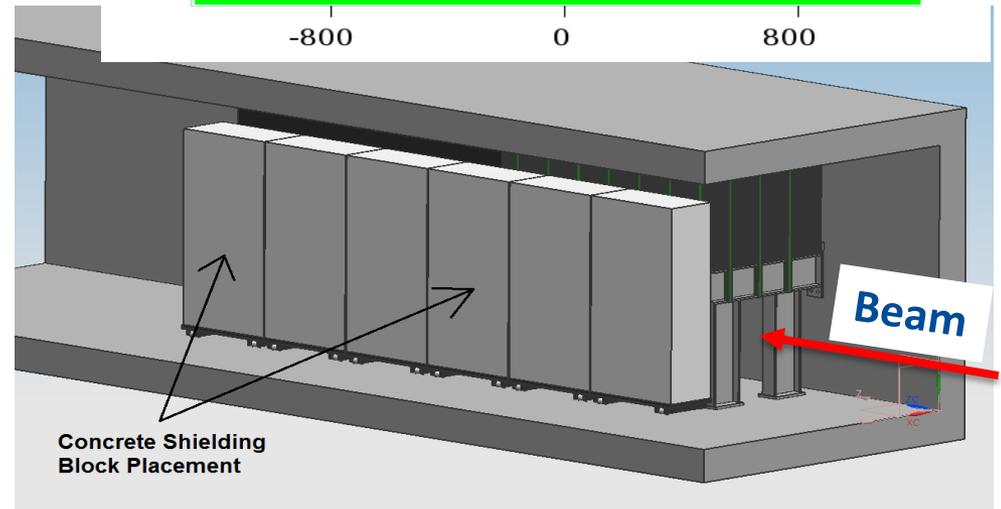
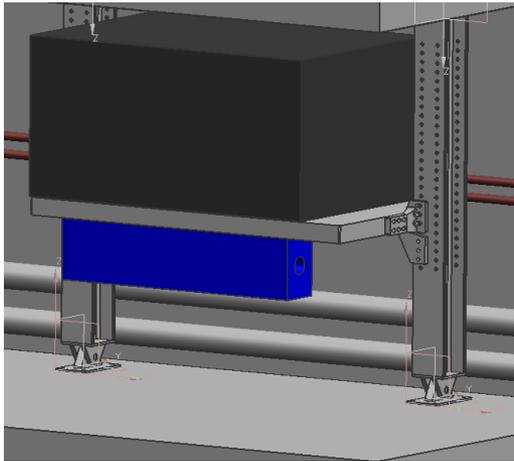
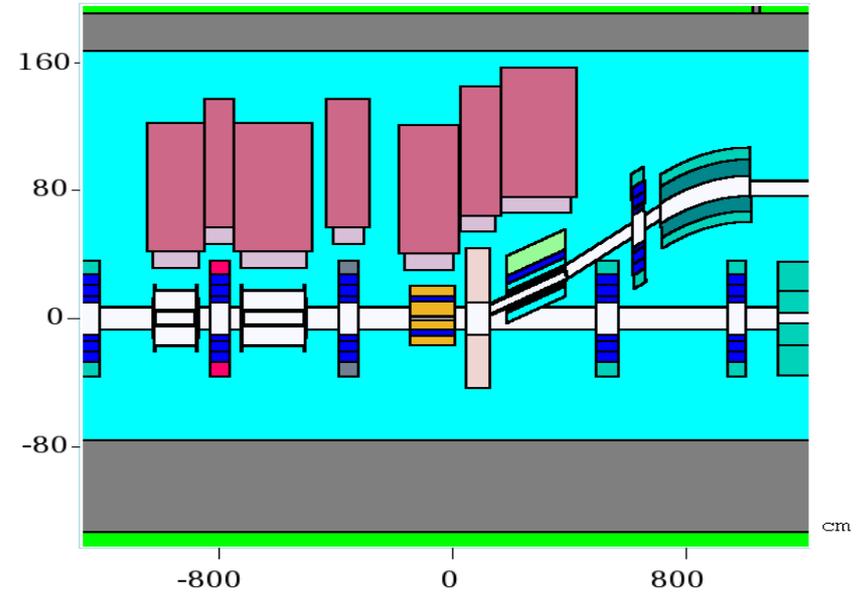


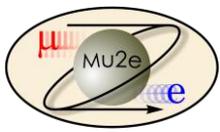
# Radiation protection

## In-tunnel shielding

- Beam enclosure has been designed for 13W 8GeV operations
- Mu2e: 8kW 8GeV beam
- In-tunnel shielding above extraction channel
- Concrete shielding in the isle
- Additional shielding if needed

Extraction channel- Elevation view

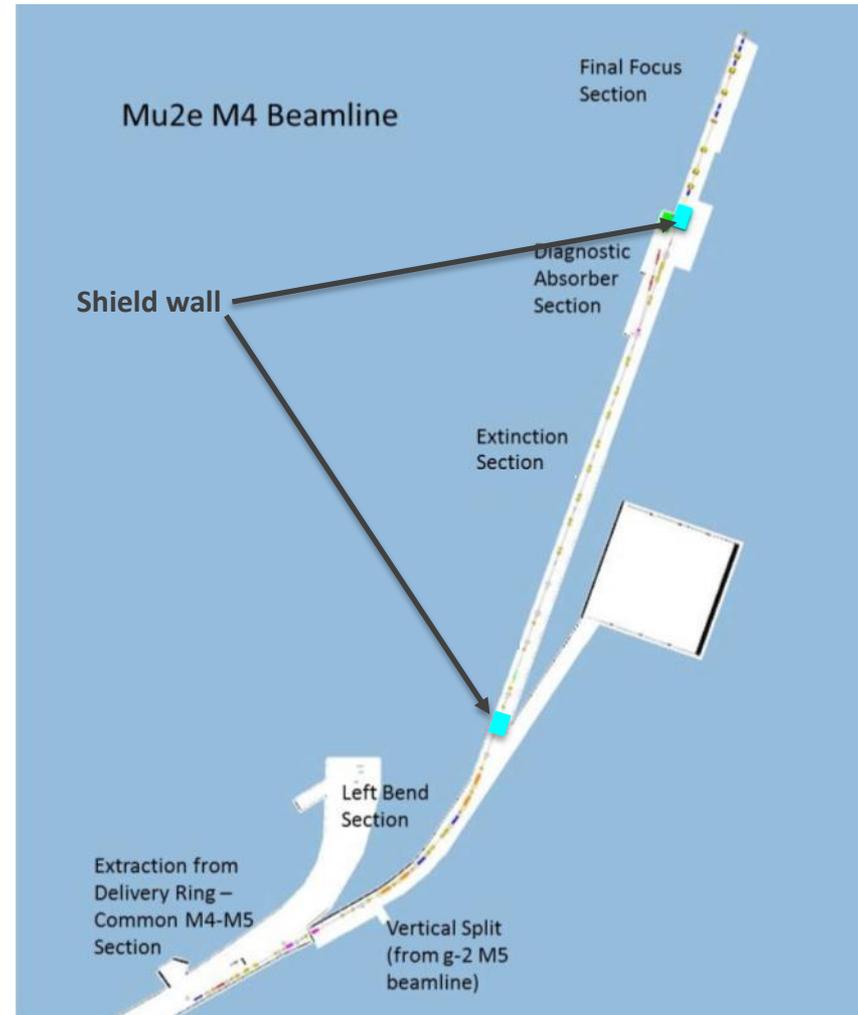


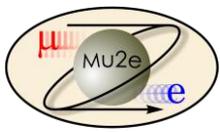


# Radiation protection

## Protection of people downstream (not in RE scope)

- M4 line enclosure protected by shielding wall during installation
- Mu2e PS hall protected by shielding wall during commissioning and g-2 operation
- G-2 protected by shielding wall during Mu2e operation

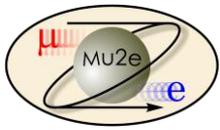




# Machine protection

## Accident case scenarios

- DR abort system is not capable to abort beam during the spill, we can only abort in the end of the spill and inhibit next one.
- Worst case scenario: loss or extraction of the whole spill intensity in a single pulse
- Beam permit system can inhibit the next spill:
  - On BLM trip
  - On Spill Monitor threshold
  - On Detector diagnostics
  - On regulation system abort signal
- Single bunch is not destructive for:
  - Septum foils
  - Production target
  - Detector systems

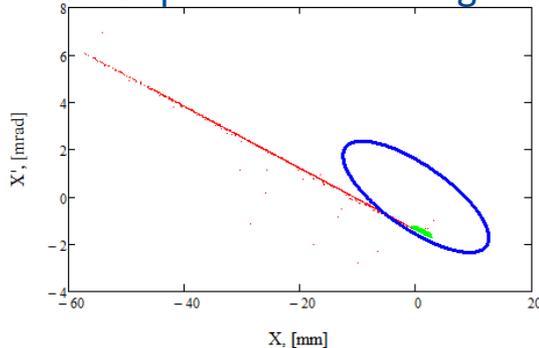


# Beam loss – local and global budget

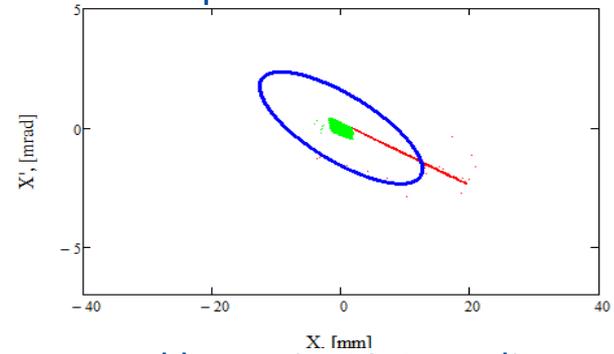


# Beam loss – local and global budget

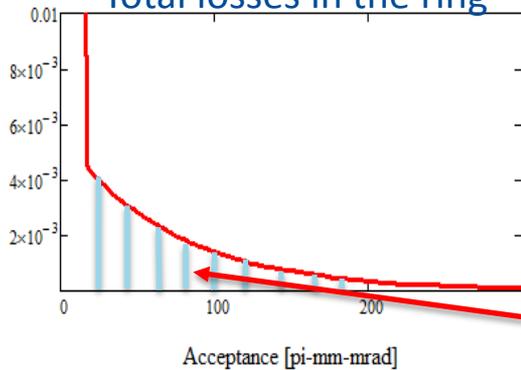
Phase space of circulating beam



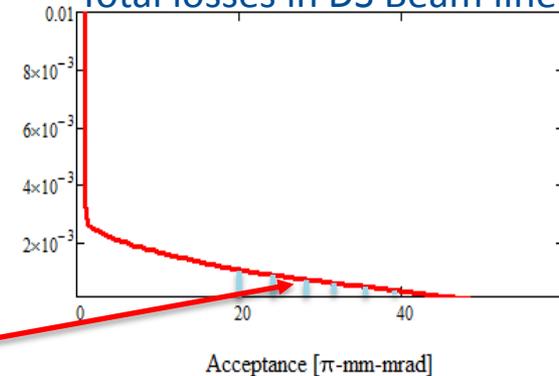
Phase space of extracted beam



Total losses in the ring

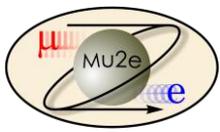


Total losses in DS Beam line

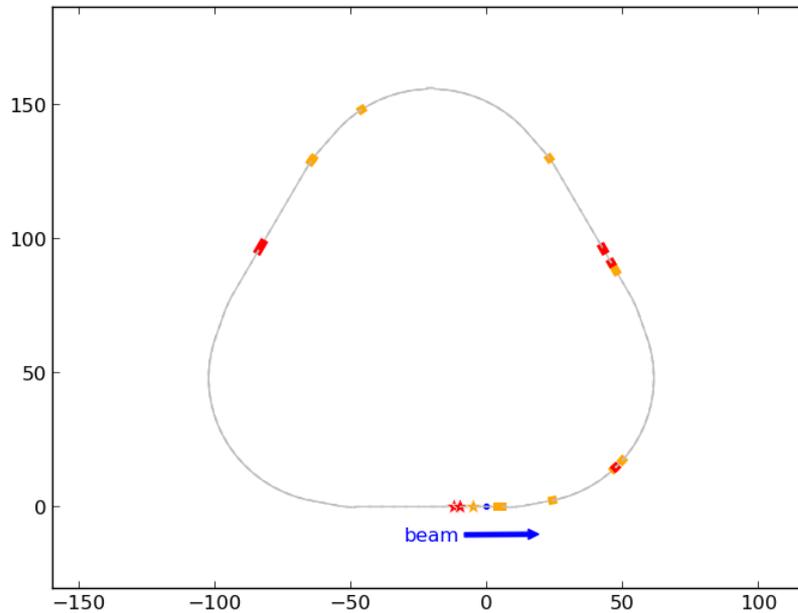


Losses  
downstream

- Local losses defined as missing beam DS of C-mag
- DS losses calculated as beam scattered outside of the 20  $\pi$ -mm-mrad area
- Total losses = Local + DS losses (nearly twice local)
- “Anything scattered is lost” ?
- Tolerance on effective thickness of the foil plane <50u



# Beam loss – local and global budget

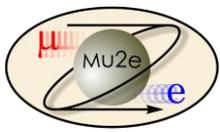


Localized losses in the ring

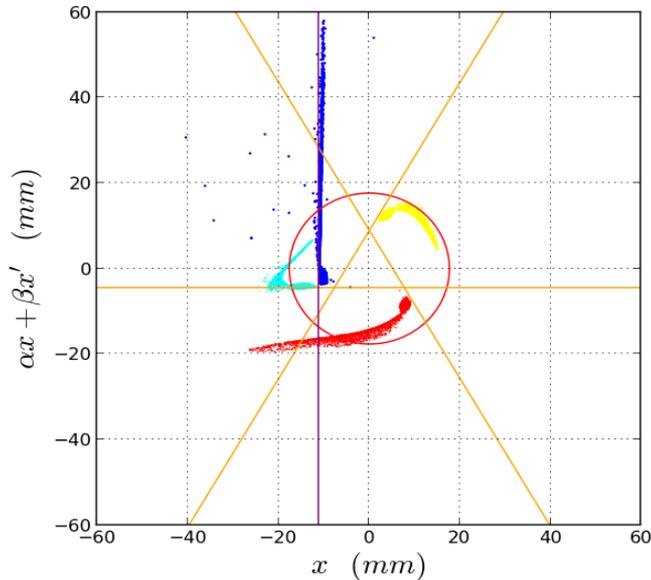
## Synergia tracking:

- 87% lost in first turn
- 99.7% lost in first 3 turns
- 40% lost before the first arc
- 16% in the first arc
- 33% in the known narrow elements

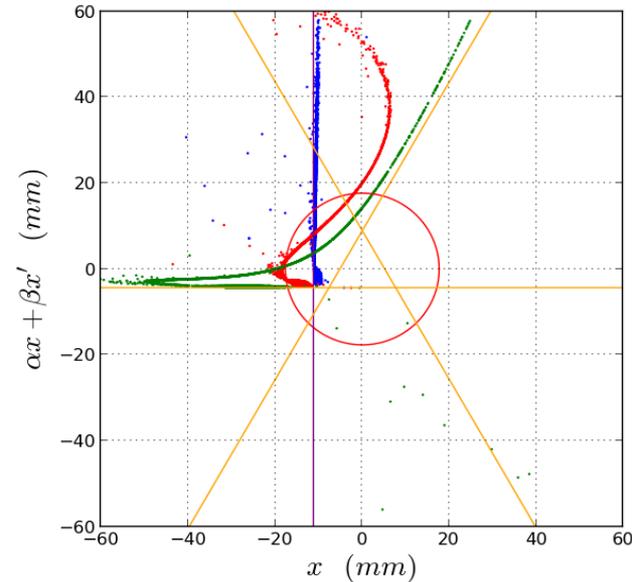
Tracking assumes idealized apertures, this breakdown just gives a general idea.



# Beam losses and related extinction issues



Scattered beam tracking



Scattered beam integration

All scattered particles are expected to be lost very quickly, so they should not contribute to out of time beam contamination.